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Mu2e/Mu2e-II: Search for Charged Lepton Flavor Violation

PIP-II

J. Miller (Boston University)

On behalf of Mu2e and Mu2e-II

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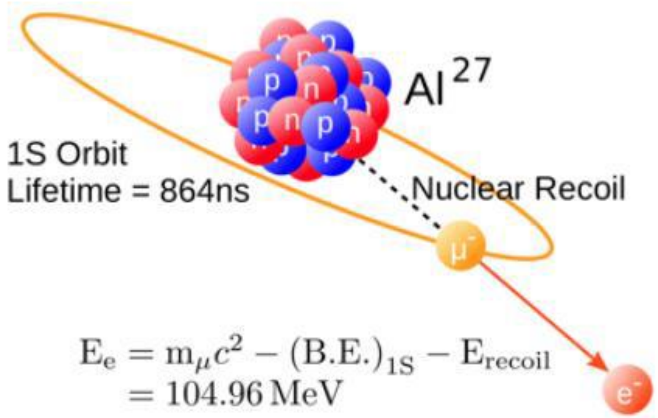
What is Mu2e?

- Search for the occurrence of neutrinoless muon to electron conversion in the near field of a nucleus

$$R_{\mu e} = \frac{\Gamma(\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al)}{\Gamma(\mu^- + {}^{27}_{13}Al \rightarrow capture)}$$



  - An example of charged lepton flavor violation
- Goal $R_{\mu e}$ (90% CL) $< 8\times10^{-17}$ $R_{\mu e}(5\sigma) = 2\times10^{-16}$ (5σ)
  - x10000 improvement on current best experimental limit
  - SM prediction is undetectably tiny, O(10^{-50})
  - Detection of a signal would be a definitive sign of new physics
- Method
  - Stop muons in a thin aluminum target. They quickly form muonic atoms in the 1s state. Search for the mono-energetic electron from muon to electron conversion
- Timescale
  - Now under construction at Fermilab
  - Run 1: in 2026 – world-leading x1000 improvement on current limit before shutdown
  - Run 2: ~3-4 years running after LBNF/PIP-II shutdown, x10000 improvement

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What is Mu2e-II?

- An upgrade to the current Mu2e experiment that
  - Is in the conceptual design phase, following the same Mu2e approach
  - Relies on upgrades to the PIP-II baseline to provide ~100 kW protons
  - Achieves an order of magnitude improvement in sensitivity over Mu2e
  - Leverages as much of Mu2e infrastructure as reasonably possible
- Timescale
  - (4+1) y of data taking at full intensity
  - Timescale under discussion with Fermilab- depends on PIP-II upgrade path
  - R&D funds on critical items

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Our goals

- Finish construction of the Mu2e experiment
- Complete Mu2e data collection
  - Mu2e Run 1 (before LBNF/PIP-II shutdown), analyze and publish results
  - Mu2e run 2 (after shutdown), analyze and publish results
- Continue R&D to develop Mu2e-II
  - develop a plan and timeline for incorporation into the Fermilab upgrade plans

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Outline

- Science Motivation
- Status and plans for Mu2e
- Motivation for Mu2e-II

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Science Motivation

- CLFV is a deep & unique probe of New Physics (NP) parameter space
  - Next generation experiments planned in Europe, Asia, and Americas
    - This program is essential in our attempt to understand LFV- we do not know the mechanism for neutrino oscillations nor do we know why we have never seen charged lepton flavor violation
  - Probes complementary regions of NP space relative to rest of HEP program
  - Comparing rates in different decay modes provides model discrimination

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3}-0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05-0.5$	$2-20$

arXiv:1709.00294v2[hep-ph]

from L. Calibbi and G. Signorelli, Riv. Nuovo Cimento, 41 (2018) 71

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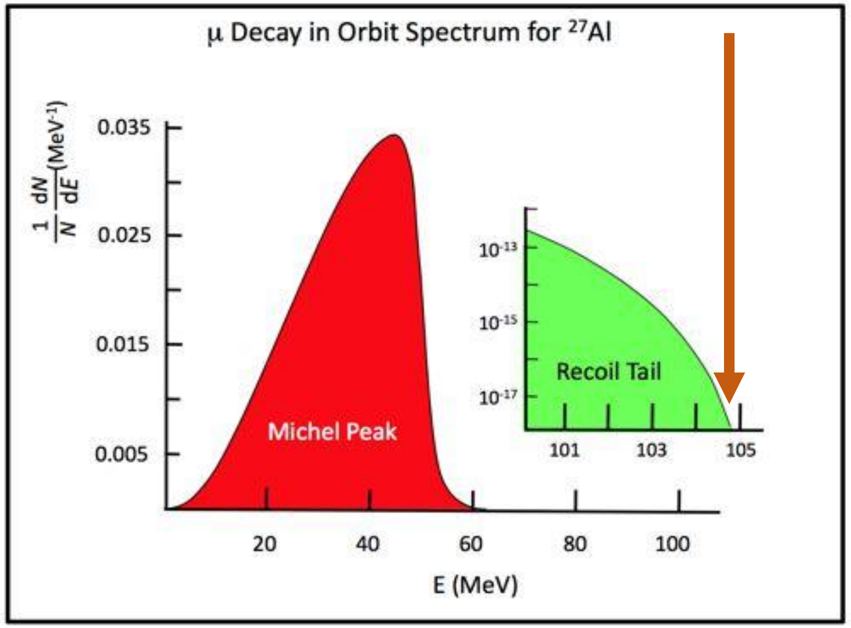
Science Motivation

- Direct μ→e conversion is the "Golden Channel" of CLFV
  - Conversion electron energy is well above most ordinary decay electrons
    - e.g. Challenge to extend μ→eγ beyond MEG-II
      - e and gamma swamped by particles from ordinary muon decays
    - Ultimate μ→e sensitivity can potentially be improved by at least an order of magnitude beyond Mu2e (see Mu2e-II)

105 MeV

$\mu N \rightarrow eN$



$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + {}^{27}_{13}Al$$

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Science Motivation

- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - $\mu \rightarrow e$ provides likely best sensitivity to CLFV across many NP models

	s	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 4.4 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \rightarrow \mu\mu\mu$	BR < 2.1 E-8	
$\tau \rightarrow eee$	BR < 2.7 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	NA62
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 2.8 E-9	LHCb, Belle II
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG-II)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-15} (μ3e Phase-I)
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0 E-13	~8×10^{-17} (Mu2e, COMET Phase-II)

(Current Limits taken from the PDG)

~6×10^{-18} (Mu2e-II)

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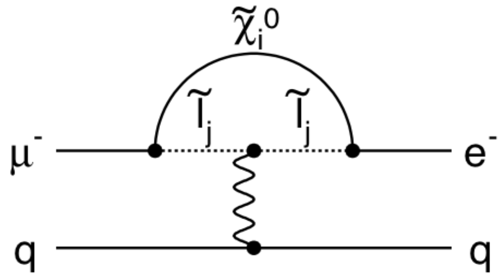
Science Motivation

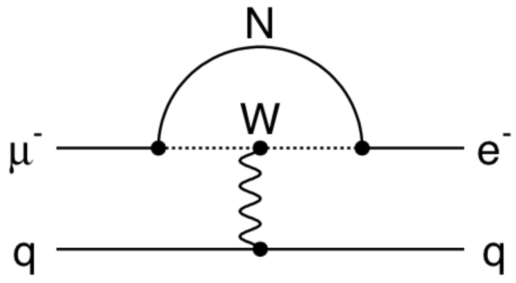
- Direct $\mu \rightarrow e$ conversion is the “Golden Channel” of CLFV
  - Sensitive to broad array of New Physics models

Mu2e comparable To $\mu \rightarrow e\gamma$

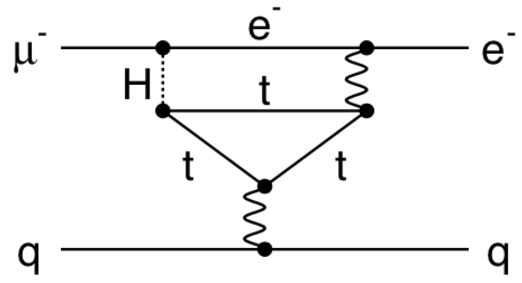
Loops



Supersymmetry



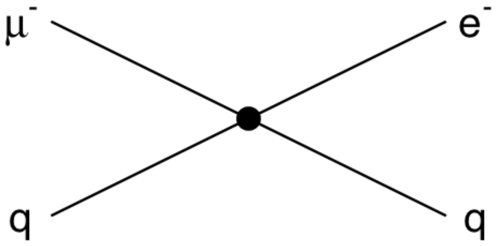
Heavy Neutrinos



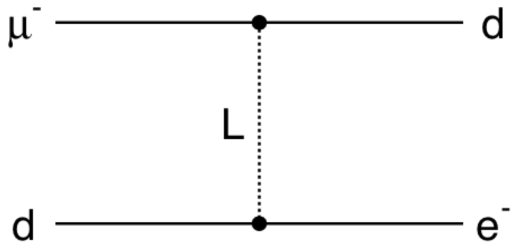
Extended higgs models

Mu2e much more sensitive vs $\mu \rightarrow e\gamma$

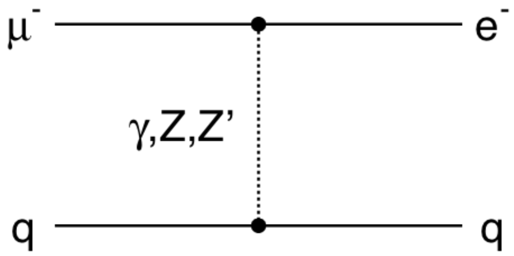
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons / Anomalous Couplings

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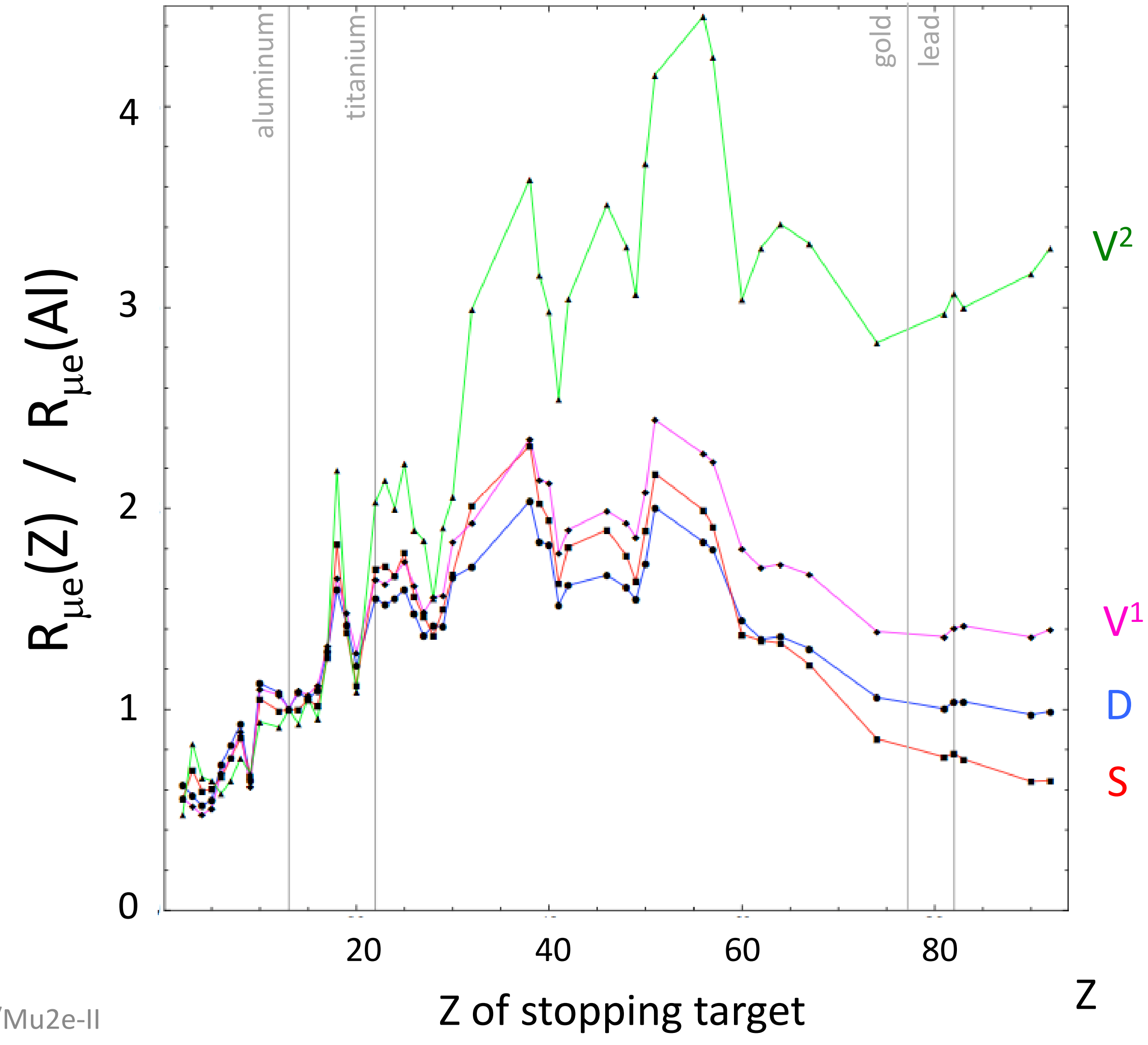
Science Motivation

- Direct μ→e conversion is the "Golden Channel" of CLFV
  - Once an observation is made, can change stopping target to probe underlying NP operator
  - Mu2e and Mu2e-II technique has limits precluding high-Z materials due to short muonic atom lifetimes
  - Examples of muonic atom lifetimes: Al (864 ns),), Ti((330 ns), Au(72.6 ns)

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



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Mu2e

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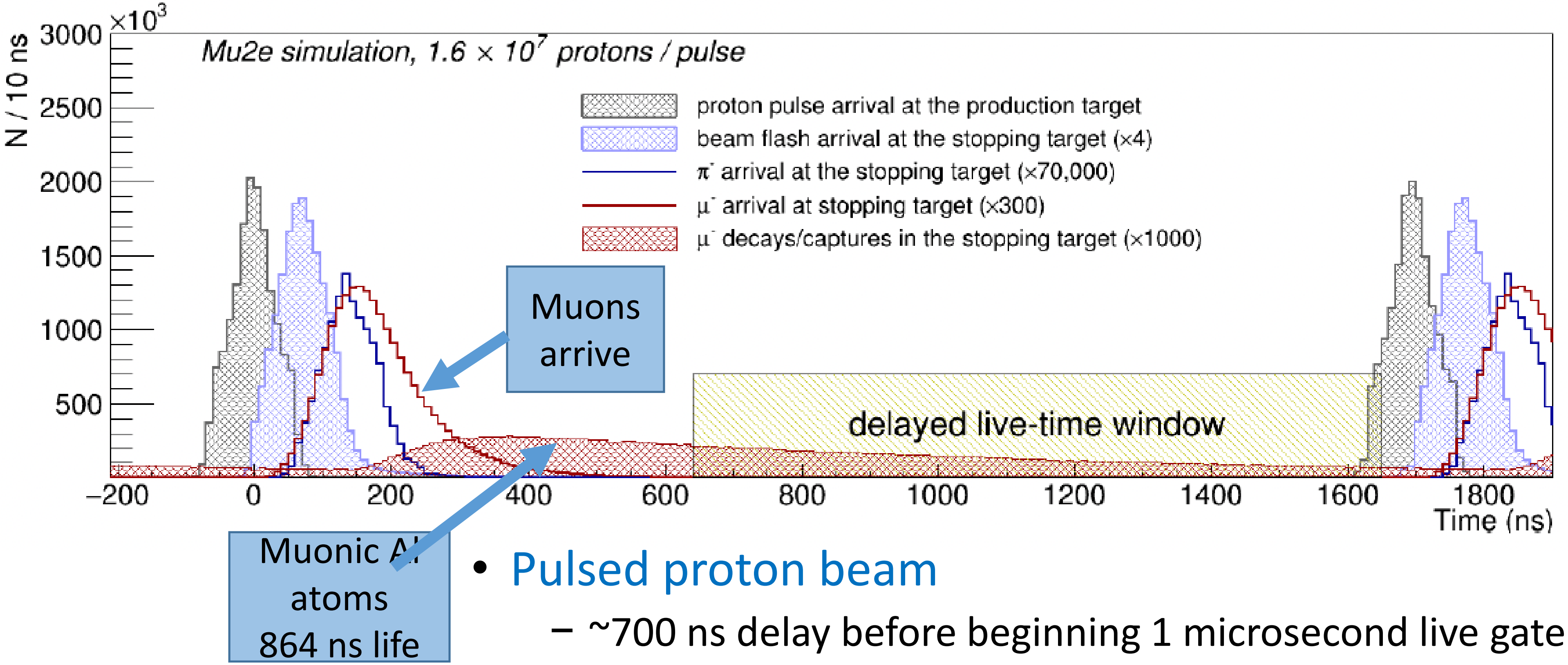
Mu2e Pulsed Beam



- Pulsed proton beam
  - ~700 ns delay before beginning 1 microsecond live gate
    - When most prompt background has died away
  - Keys to x10000 improvement: pulsed beam and Fermilab intensity
- Extinction factor (rate of out-of-time protons) of 10^{-10} is required for Mu2e

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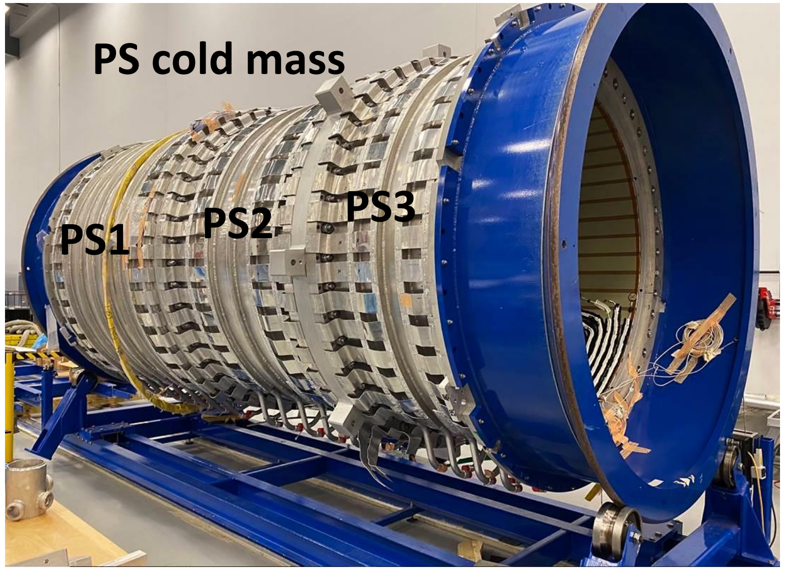
Mu2e Solenoids

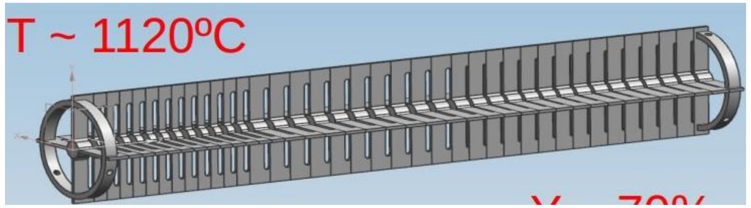


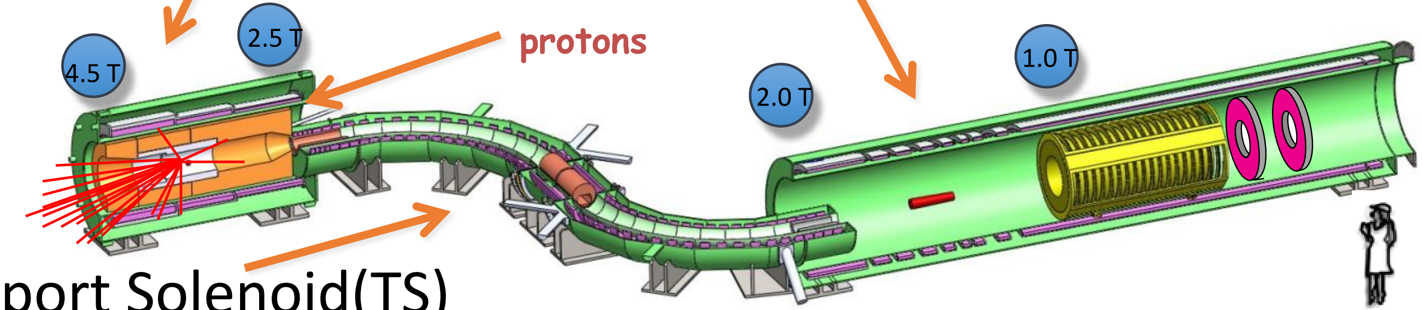
Production Solenoid(PS)

- All 3 PS coils wound
- Assembled on cold mass
- Solenoid delivery from vendor Fall 2023

Detector Solenoid(DS)

- 10/11 DS coils wound and prepared for cold mass
- Delivery to Fermilab expected Spring 2024

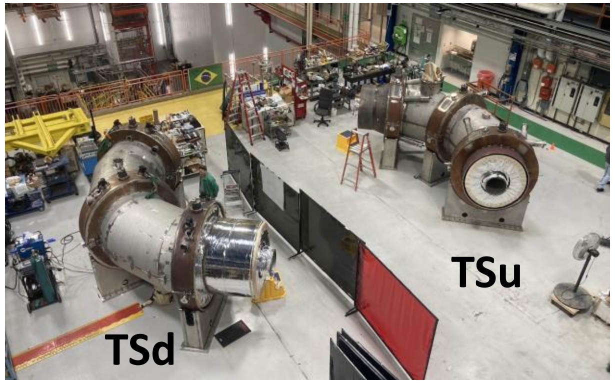




Transport Solenoid(TS)

Assembly nearing completion

Delivery to Mu2e hall expected Fall 2023



DS11 being wound

ProductionTarget

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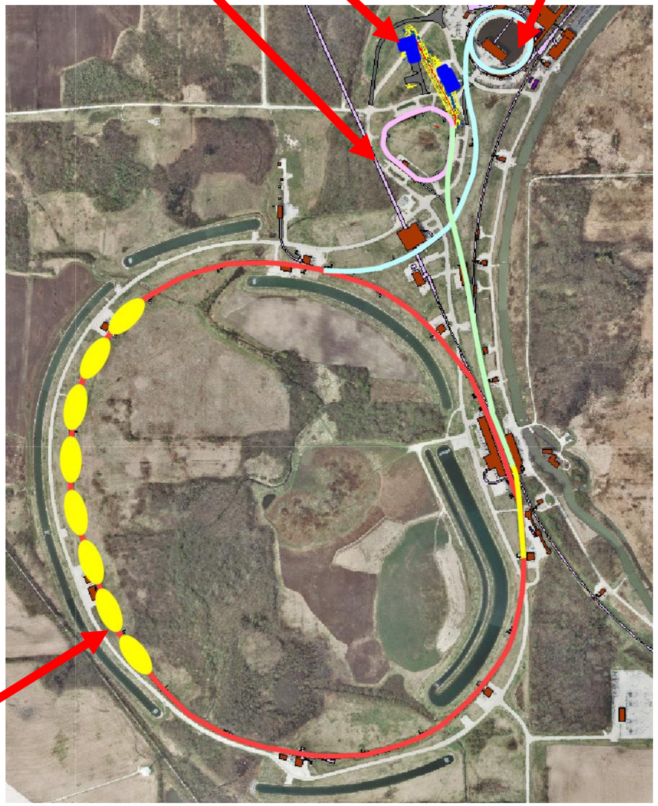
Mu2e Proton Beam

- 8 GeV 8 kW Pulsed proton beam for 0.4 s of 1.4 s Booster cycle
- ~90% of Mu2e beam elements in place
- Studies of beam under way now
  - Successfully stored and extracted single bunch 8 GeV protons to Diagnostic Absorber
- Resonant extraction- extract beam from Delivery Ring
  - First of two Electrostatic Sept (ESS) installed and testing of resonant extraction is just starting

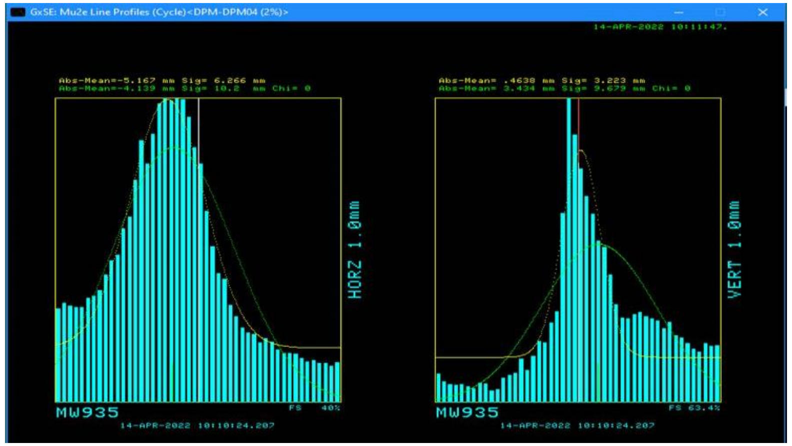
Delivery Ring

Mu2e Target

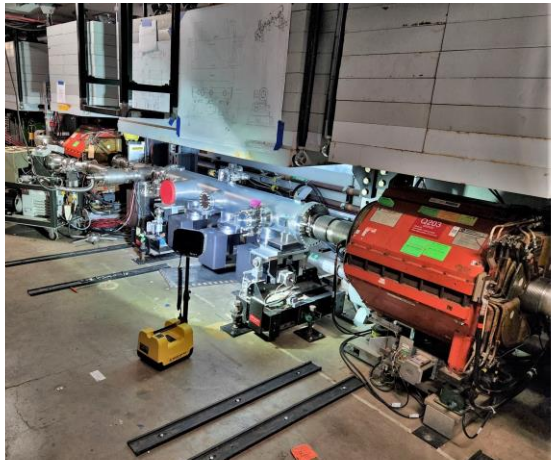
Booster



Recycler



8 GeV Beam profile at Diagnostic Absorber



Electrostatic Septum Installed

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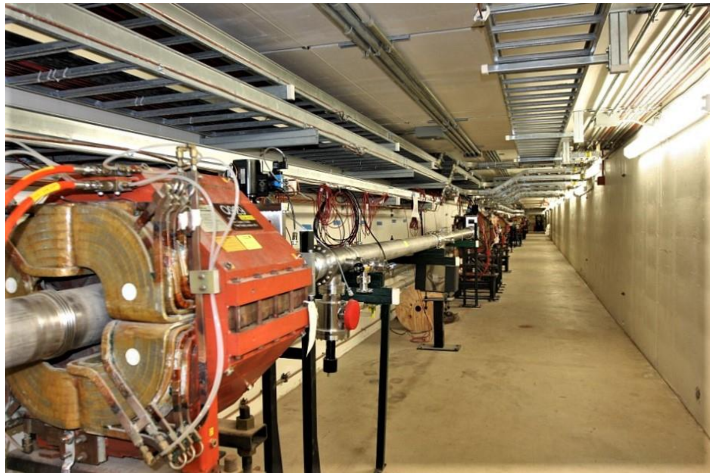
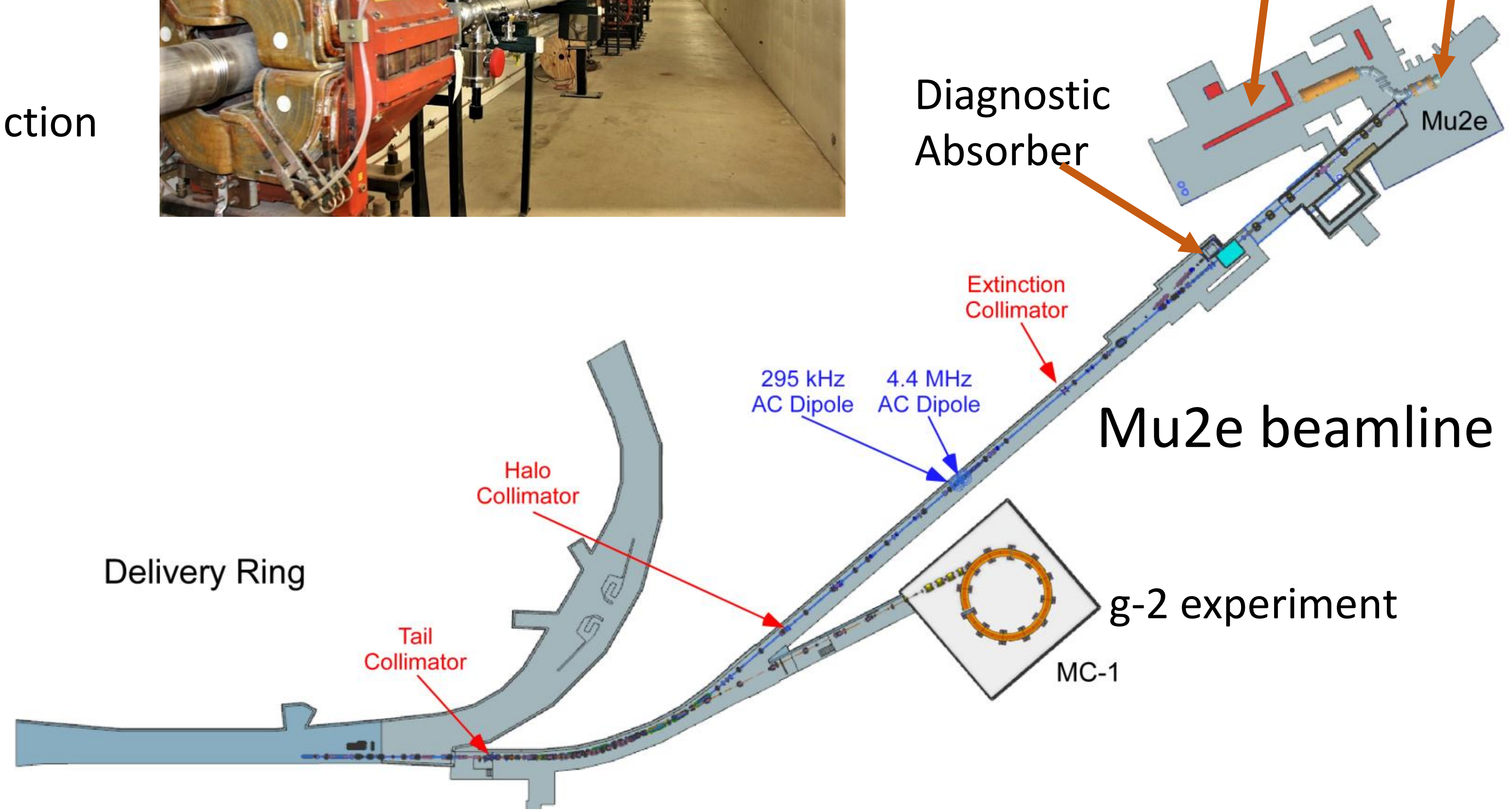
Mu2e M4 Proton Line

- Ongoing beam studies at low power to Diagnostic Absorber
- Mu2e requires extinction < 10^{-10}
  - Intrinsic accelerator extinction
  - AC resonant dipole sweepers
    - Ferrites in hand
    - Vacuum chambers under construction at vendor and Fermilab
- Expect ~10^{-11} overall



- M4 Beamline Complete and operational up to the Diagnostic Absorber
- Remaining scope:
  - Fabrication and installation of AC Dipole magnets and power supplies
  - Downstream end of M4 Final Focus vacuum system



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Detectors

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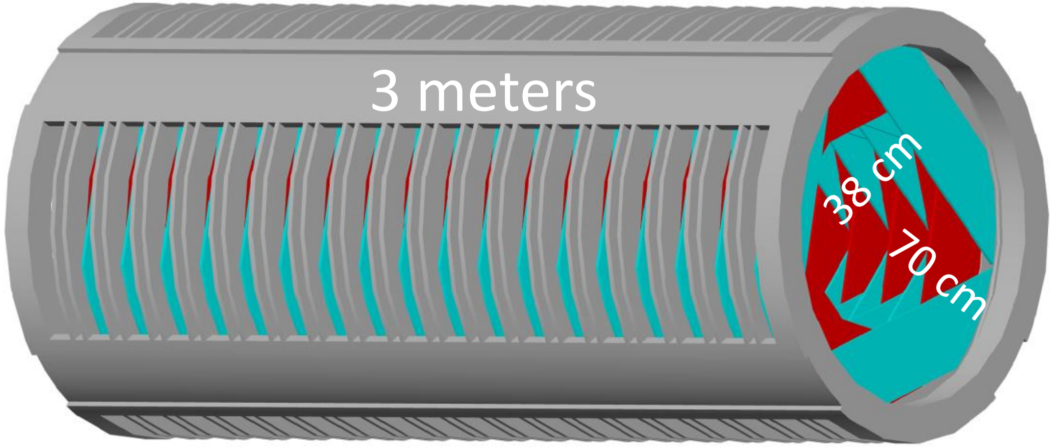
DIO Electrons and Tracker

- A Tracker is employed to measure the conversion electron momentum
- Electrons from muons decaying in atomic orbit (DIO) are mostly below 53 MeV
  - Central aperture in Tracker (and calorimeter) avoids copious DIO electrons with E<53 MeV, yet maintains good acceptance for the high energyconversion electrons
- But there is a high energy tail to DIO electron distribution
- Excellent resolution required to reduce DIO background σ~140 keV/c for 105 MeV/c electron

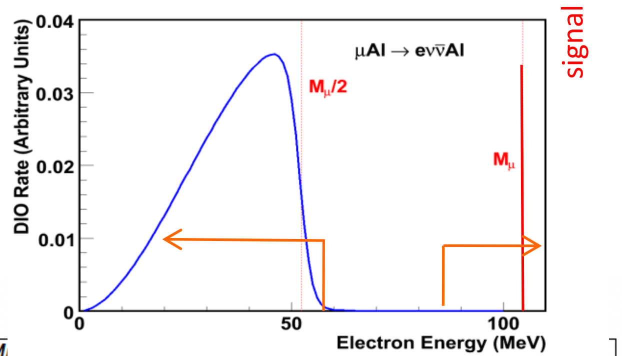
DIO electrons arise from ordinary decays of muon in atomic orbit

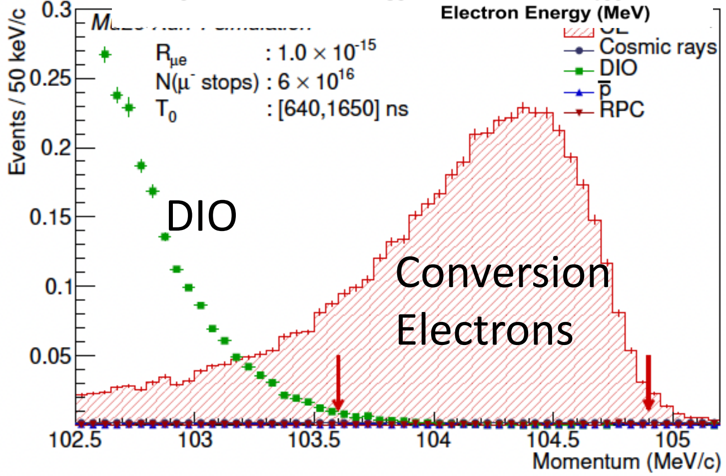
$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + {}^{27}_{13}Al$$

A small high energy tail extends up to conversion electron energy



Tracker





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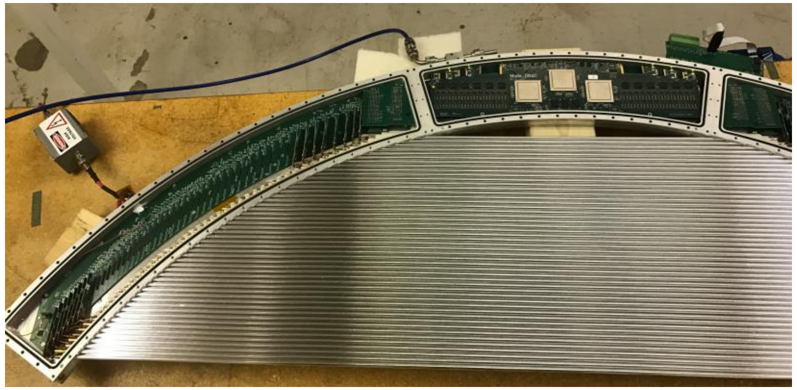
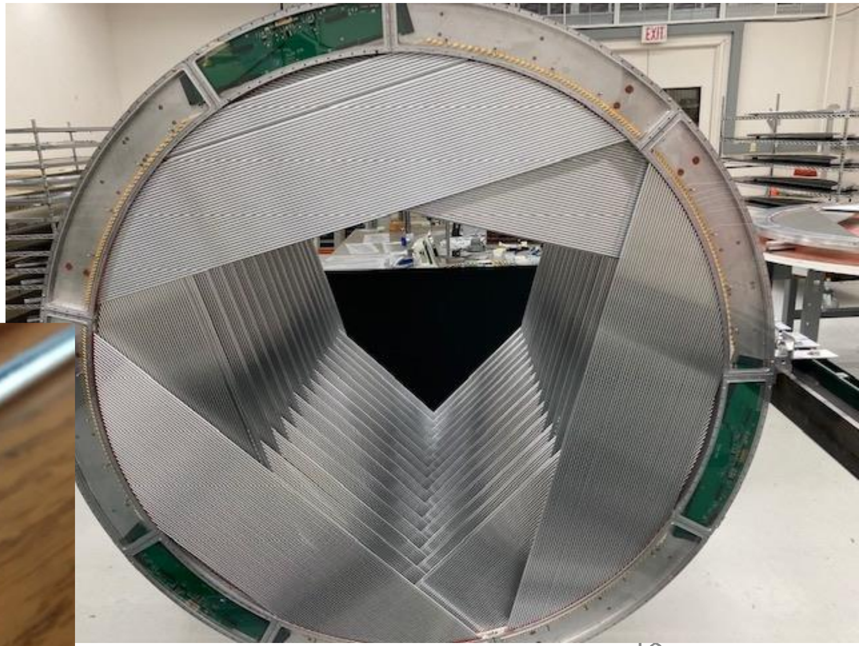
Mu2e Tracker

- 21000 straws, 96 per panel interleaved in two planes
  - Straws: 15 micron walls, 25 micron W wires
  - All 216 Panels + spares complete
  - 22 of 36 Planes assembled, to be arranged in 18 stations of pairs of planes
- Successful vertical slice tests on a plane with cosmic rays
- Electronics
  - COVID-related supply chain delays are easing
  - All FPGA's recently acquired
  - Enough electronics will be available shortly to fully test several stations- cosmics
- Completion expected March 2025



Panel w/Front-End Electronics



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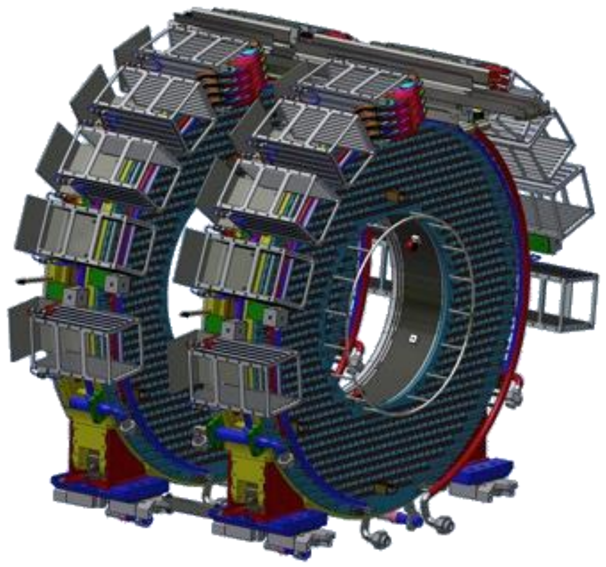
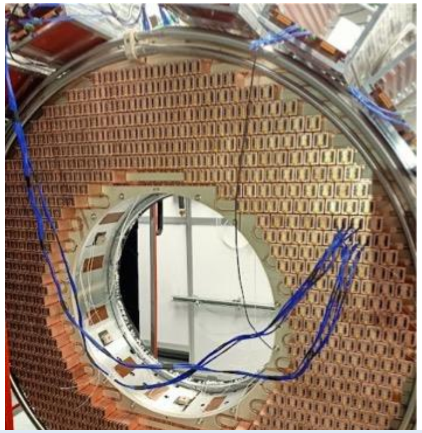
Mu2e Calorimeter

- 2 annular disks. Each with 674 pure CsI crystals + 1348 SiPMs
- FEE on SiPM pins + digital readout on crates
- Complements the tracker for μ/e PID + triggering and support on track-seeding
- Resolution requirements for 100 MeV electrons: < 10% energy, < 500 ps timing, < 1 cm position
- Assembly at Fermilab under way, installation at Mu2e Spring 2024
- Large Italian contribution

- Crystals, SiPMs, FEE, mechanics completed.
- Source + Laser system under installation
- Production of Digital electronics underway
- Installation tooling and services in progress





Full Disk assembled with Readout Units (SIPM/FEE)

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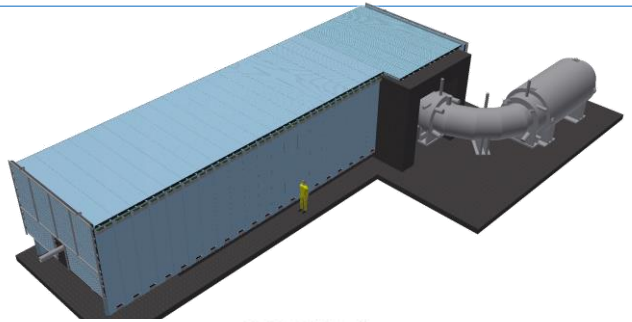
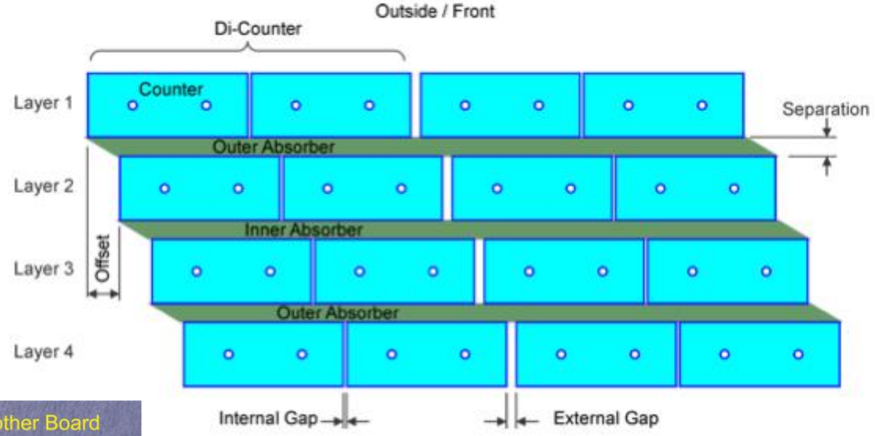
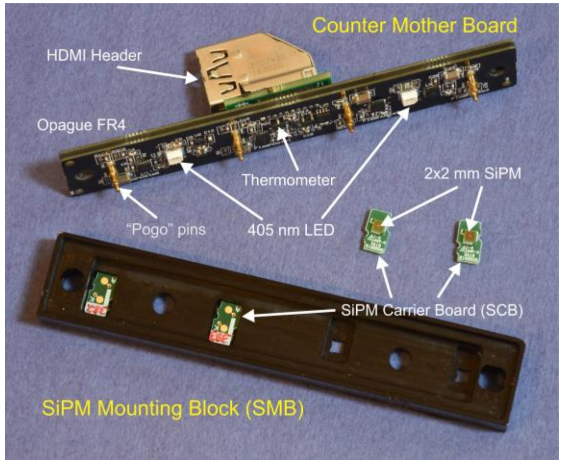
Mu2e Cosmic Ray Veto

- Cosmic ray veto (CRV) detector surrounds the Detector Solenoid - needs to be 99.99% efficient
- Module
  - 4 layers extruded polystyrene scintillator counters w/ embedded wavelength-shifting fibers, SiPM readout
- Modules 96% complete
  - 80/83 complete- composed of 16 5cmx2cm ranging 1m to 6m long
- Electronics
  - All SiPMs and FEE in hand. Most parts in hand for digital boards except for FPGA's
  - Now receiving FPGA's to complete electronics after supply chain issues
  - DAQ V1 tested successfully







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Mu2e Mock Data Challenge

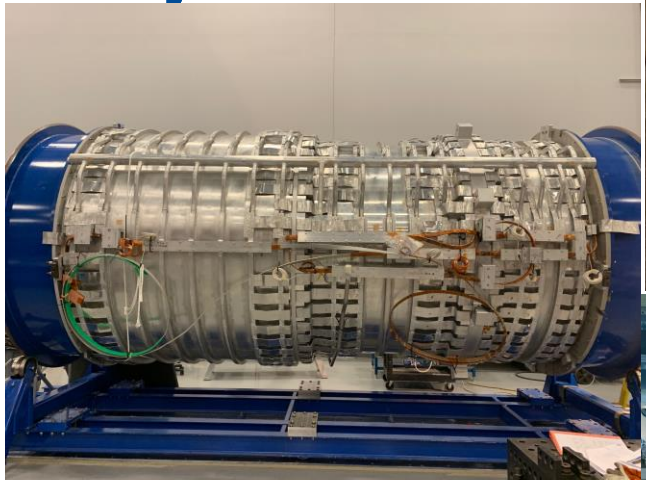
- Detailed simulation model of Mu2e data for Run 1, starting at detector hit level

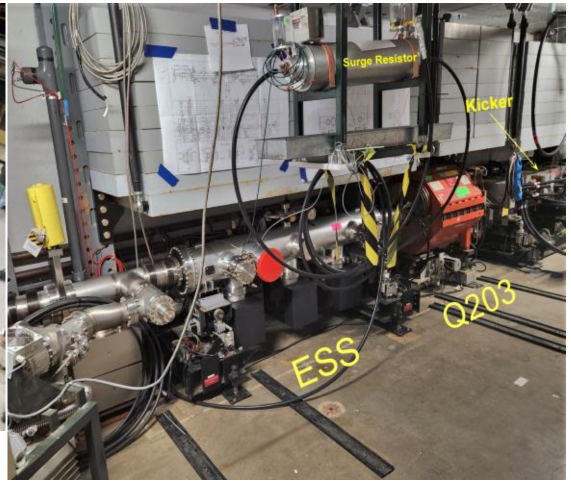
Table 8. Background summary and SES using the optimized signal momentum and time window, $103.60 < p < 104.90$ MeV/c and $640 < T_0 < 1650$ ns.

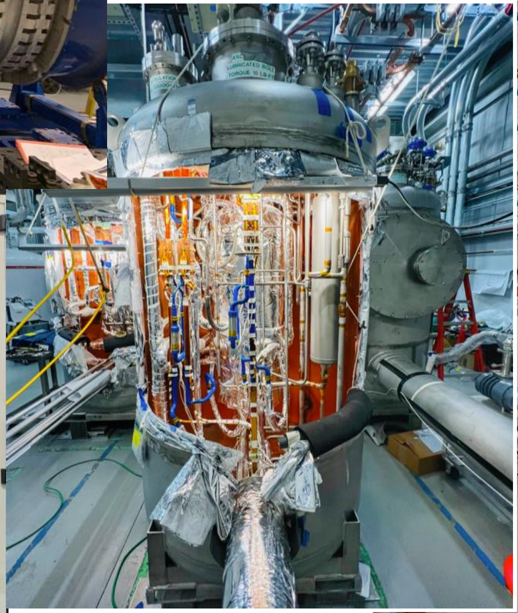
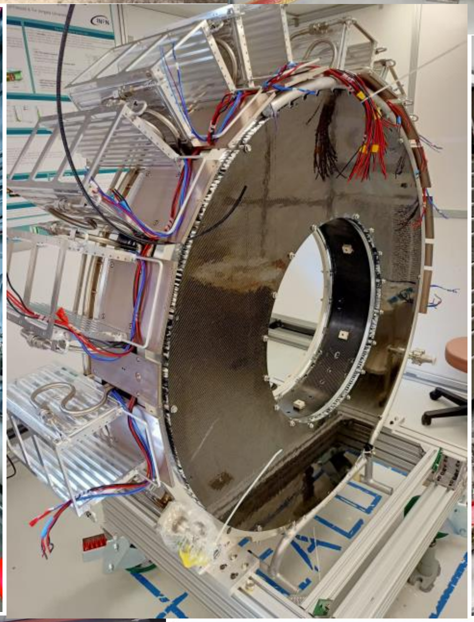
Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (syst)$) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

arXiv: 2210.11380
October 2022

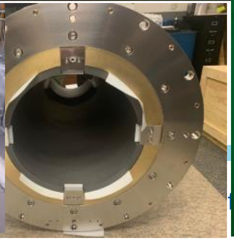
Project Status

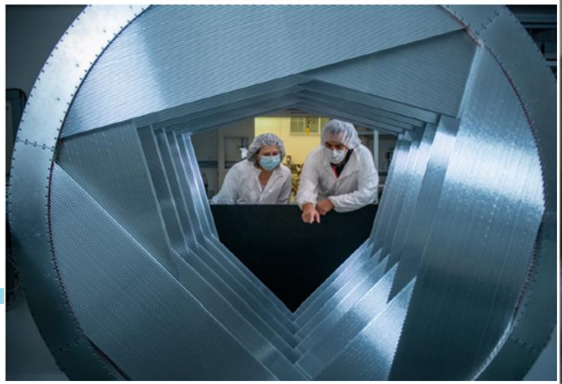
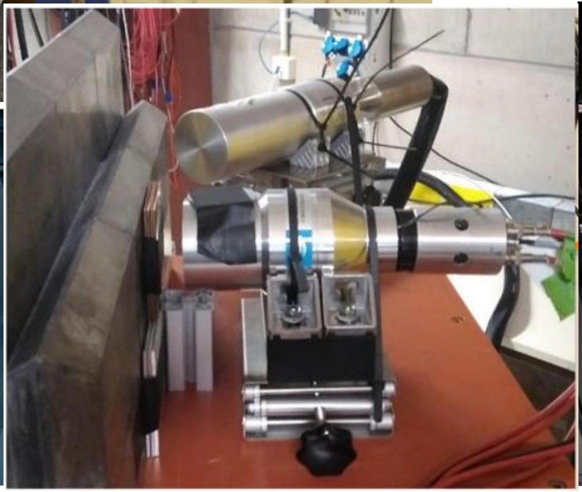




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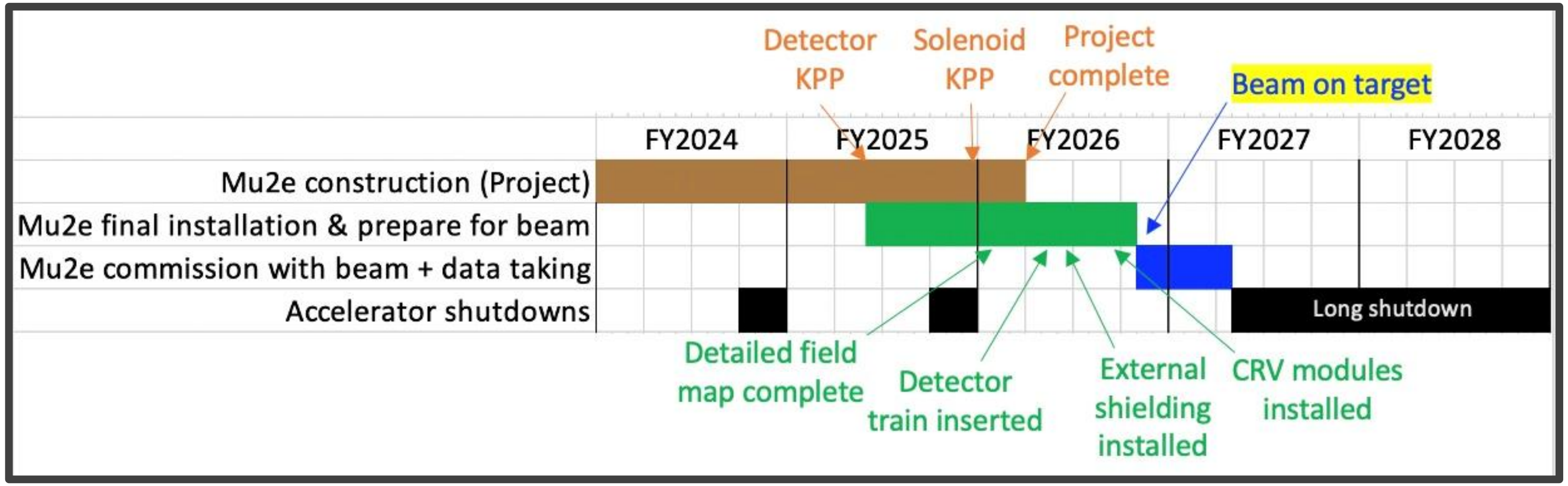
Mu2e Timeline

- Mu2e Project is fully funded and 85% complete
- High priority and high level of support from Fermilab
- Aiming for Project early completion date Dec 2025
- Begin Run 1 data taking mid- CY2026 - for about 6 months of data collection



- Resume data collection after shutdown and collect data for 4 years
- Request P5 endorsement of physics and for operations and collaboration support

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Summary Mu2e

Mu2e will produce x10000 improved sensitivity to muon to electron conversion

- **Strong endorsement from P5 in 2014**
  - “Recommendation 22: Complete the Mu2e and muon g-2 projects"
- **Important component of the Fermilab program into the next decade**
- **Major step forward in the search for charged lepton flavor violation**
  - Provides one of the deepest probes of NP related to CLFV
- **Run 1 scheduled in 2026 before LBNF/PIP-II shutdown**
  - Goal: 10% of total data set and x1000 improvement in sensitivity over present experimental limit
- **Run 2 after LBNF shutdown expects to reach final x10000 goal in 4 years of running**
- **Asking P5 for strong endorsement of Mu2e physics goals**

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Mu2e-II

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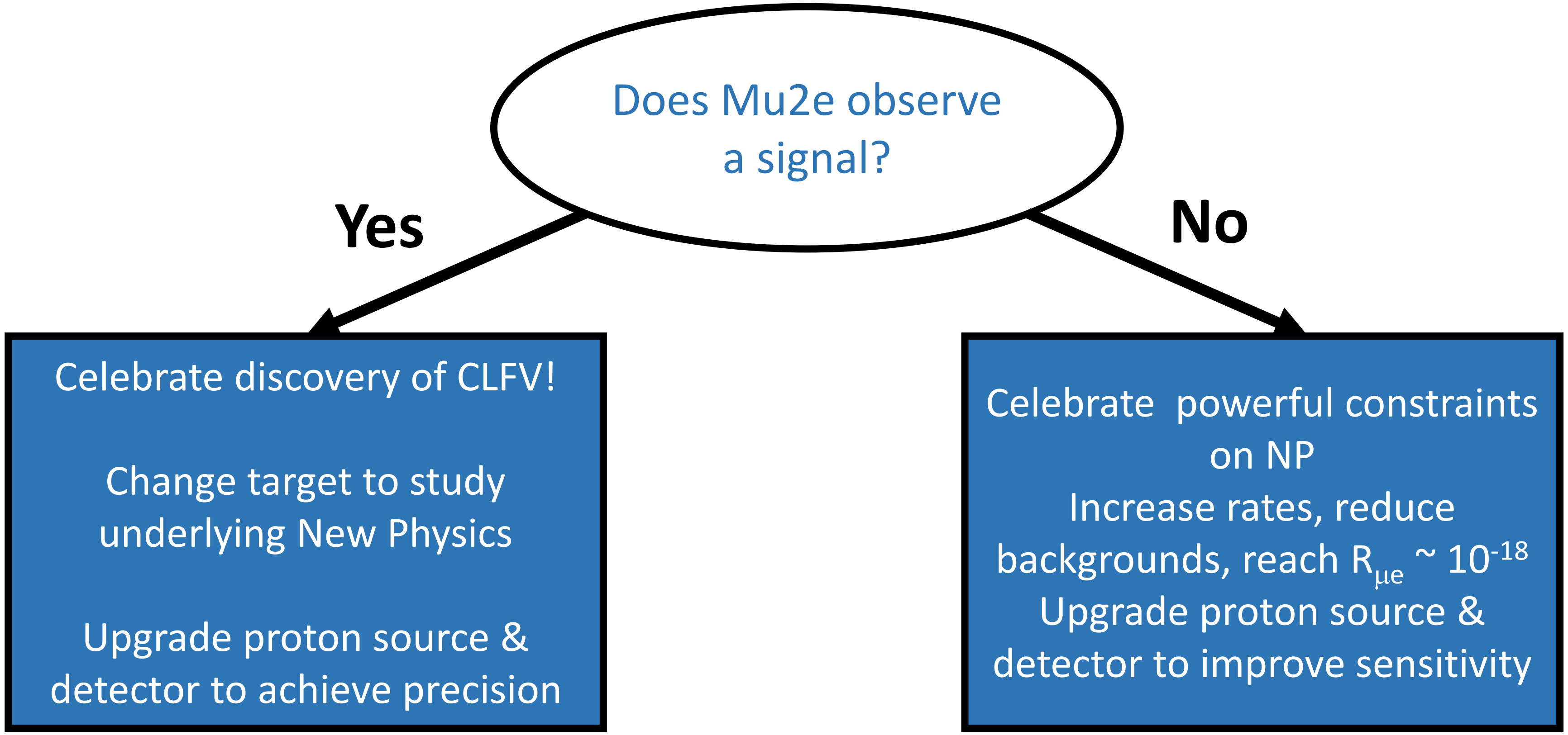
Mu2e-II Motivation



- **At conclusion of Mu2e there's a strong motivation to upgrade proton source and detector to further pursue New Physics – Mu2e-II**

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Mu2e-II

- One order of magnitude improvement over Mu2e
- Retain as much of Mu2e infrastructure as possible
- Made possible by increased beam intensity from upgrades to PIP-II (8 kW → 100 kW)
- Works well at 800 MeV (same muon stops per watt as 8 GeV)
- Would benefit from higher muons/watt at 2 GeV
- Needs R&D support to advance conceptual design

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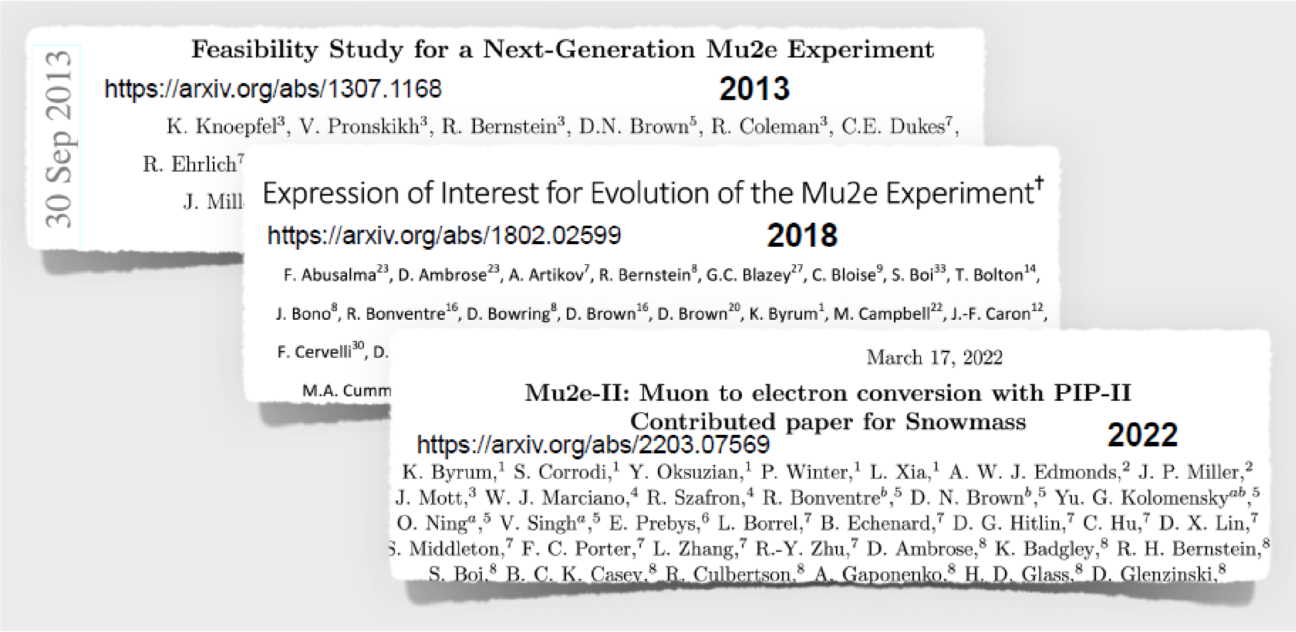
Mu2e-II Experimental Concept

- Mu2e-II Experimental concept is a natural extension of Mu2e
- Studies of feasibility started a decade ago
  - Since then multiple workshops and several study papers
- Expression of Interest submitted to Fermilab PAC 2018
  - PAC recommended support for high-priority R&D items
- 2 LDRD's: production target and tracker
- 12 LOI's on Mu2e-II subsystems submitted to Snowmass21
- Snowmass21 White Paper arXiv:2203.07569
  - 108 signatories from 34 institutes and 7 countries
  - Snowmass 21 endorses the physics goal and recommends Mu2e-II as natural progression in the muon program

Meeting at Caltech next week: "Future Muon Program at Fermilab"



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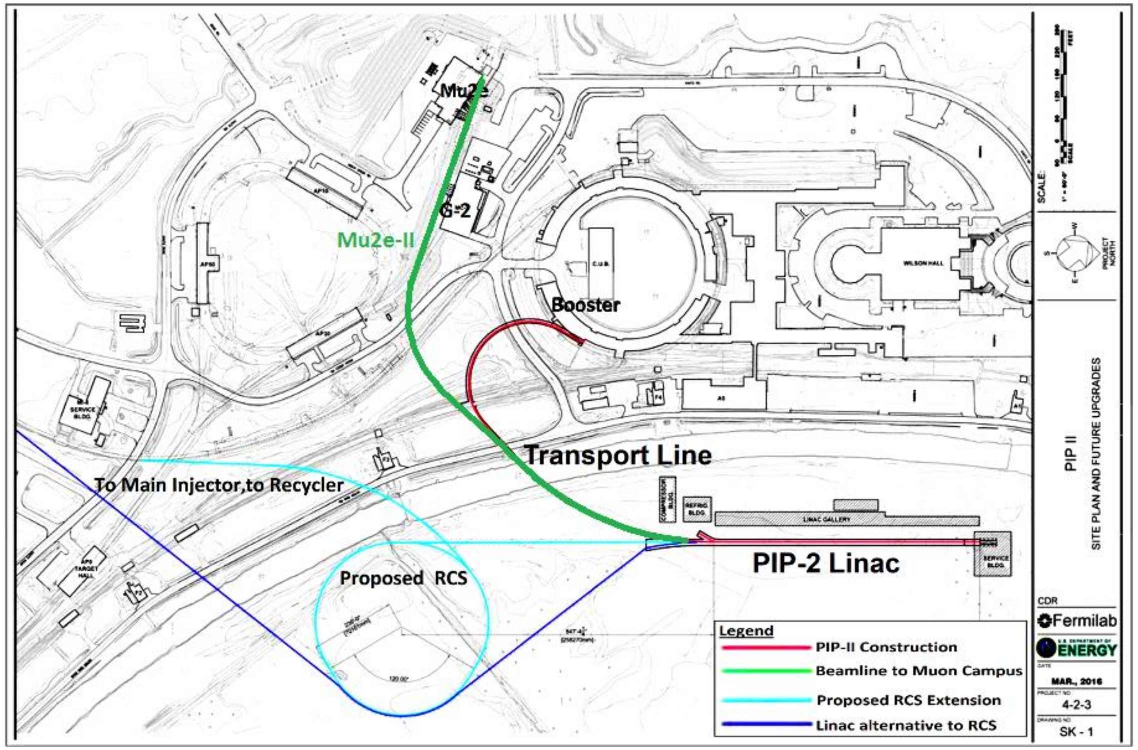
Mu2e-II: Protons from PIP-II

- Needs upgrade of PIP-II to provide beamline
  - Eliminates Booster-Recycler—Delivery Ring and resonant extraction
  - Expect more stable pulse intensity and less halo
- Can use any PIP-II Linac energy under discussion (0.8-2 GeV, higher E better)
- PIP-II has flexibility in the delivered pulse structure- neutrino program uses only a small fraction of Linac



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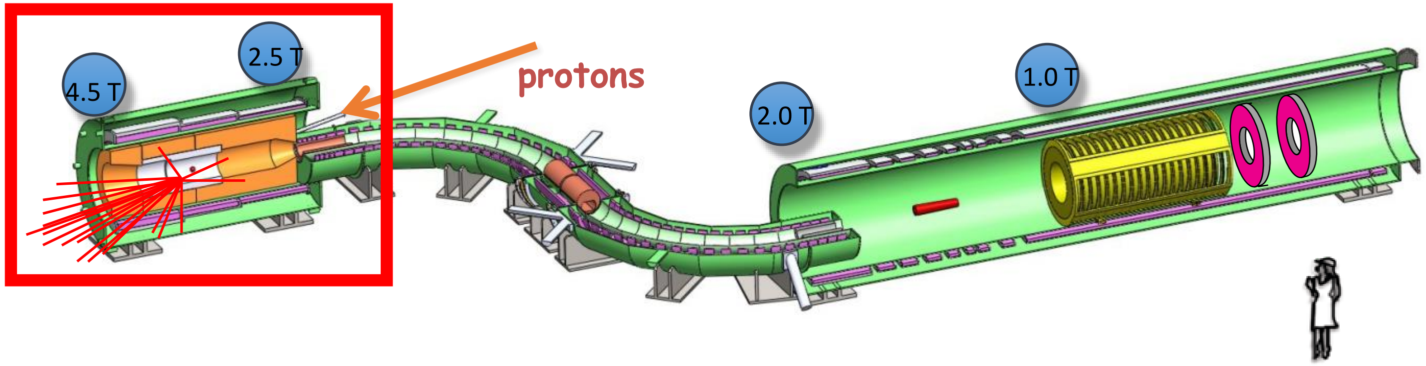
Mu2e-II: Production Solenoid(PS)

Mu2e-II: 100 kW protons for Mu2e-II versus 8 kW for Mu2e

Challenges

- Design a target that can handle very high heat and rad loads
- Replace bronze heat and radiation shield with tungsten shield
- Entire PS may have to be replaced due to activation and rad damage
- Protons curve in field, injection path must be modified
- Proton beam dump will have to be moved
- Overhead shielding must be substantially increased for rad safety



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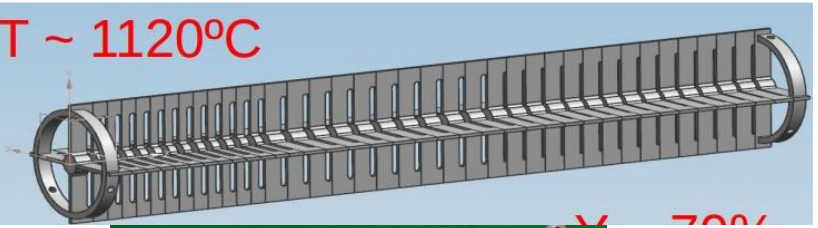
Production Targets

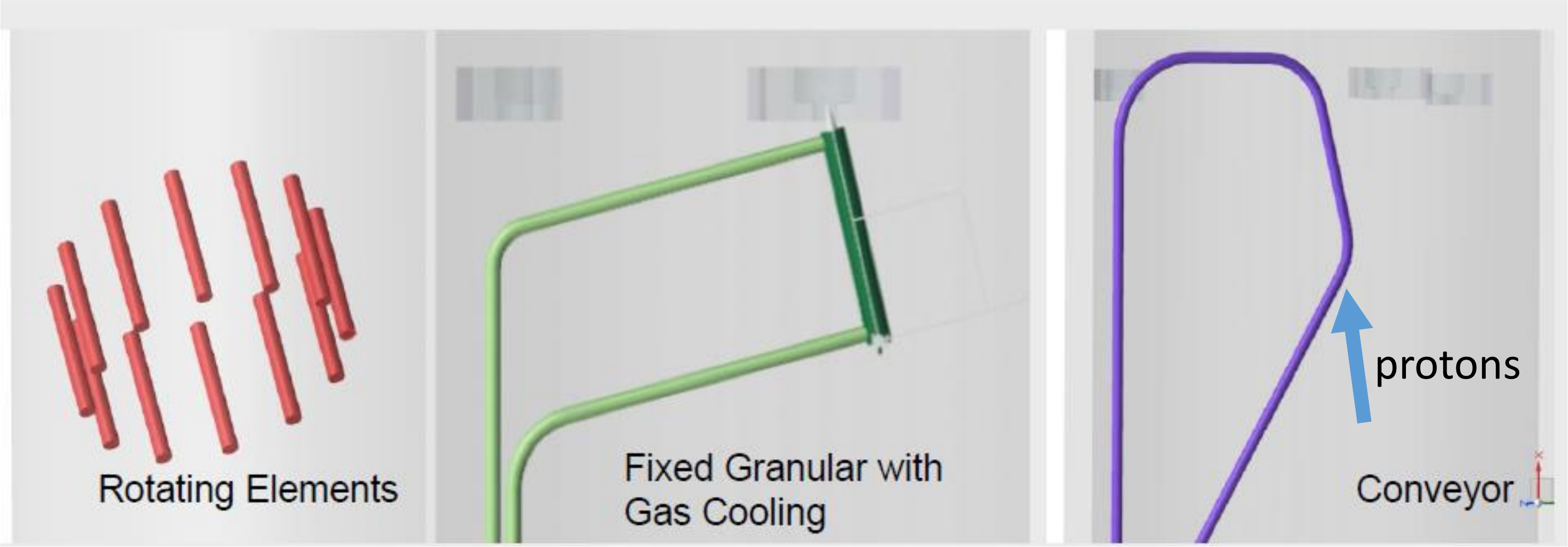
Mu2e Production Target

- Radiatively cooled W with fins
- Supported by ‘bicycle spokes’



Mu2e-II Candidate targets

- Fermilab LDRD supports target investigations
- Conveyor prototype is current front-runner
- Second prototype just arrived
- Simulations ongoing of muon yield, thermal stress, radiation damage, residual activation, radiation and heat loads
- Synergy with other target groups e.g. muon collider and AMF are being discussed, including discussion of liquid metal targets
- The Muon Collider and Mu2e-II target teams are attending each others workshops



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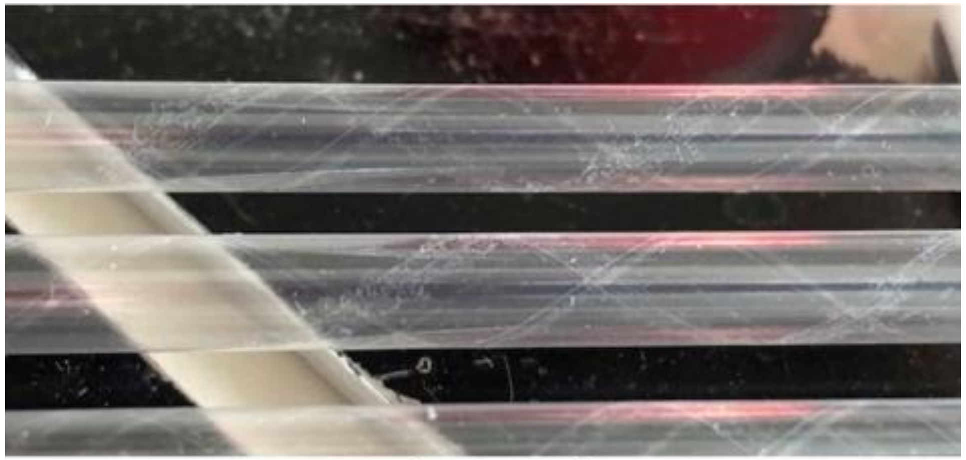
Mu2e-II Tracker R&D

- Decay in orbit electron background increases x10
  - Improve resolution of Tracker by reducing its mass
- LDRD at Fermilab supporting effort to evaluate options for improved tracker
  - Reducing straw thickness, 15 microns (Mu2e) to 8, improves resolution from 140 keV to 100 keV
  - Ongoing studies of prototype straws, investigating challenges with vacuum tightness, long-term stability, and large scale production.
  - Also investigating other options such as drift chambers
- Integrated rad dose levels will be x10 that of Mu2e- ~Mrad and 10^{13} (1 MeV equiv.) n/cm^2
  - Studies of rad-hard electronics
  - may require custom ASIC's



Pressurized 8 μm Mylar Straws

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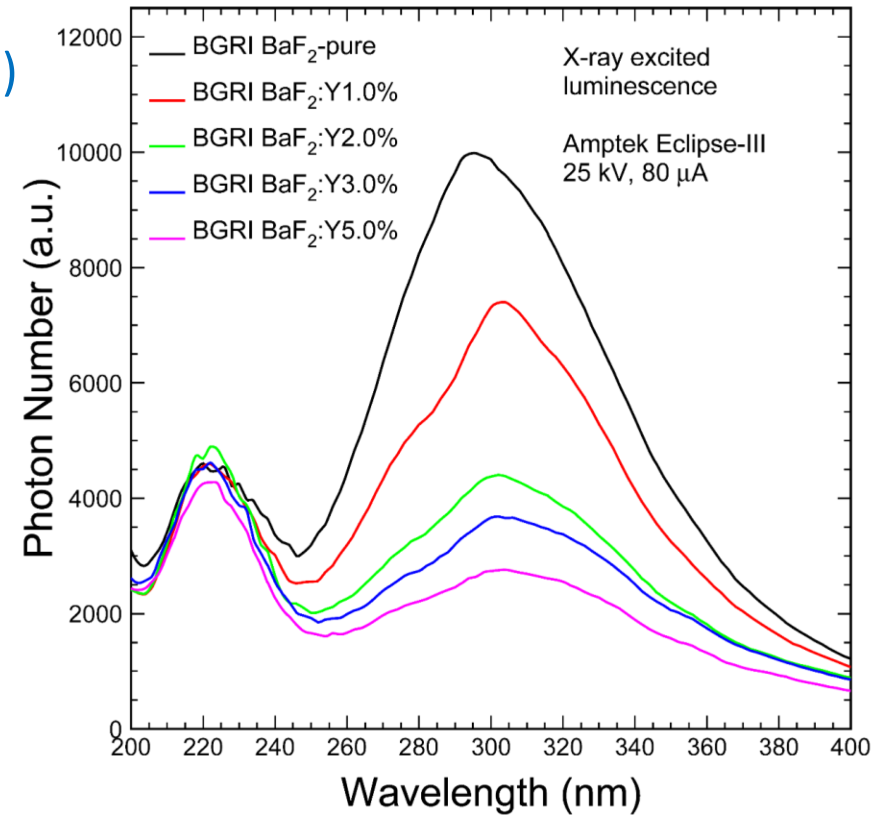
Mu2e-II Calorimeter

- Mu2e crystals CsI can't handle rad doses and occupancies at Mu2e-II in first disk, second disk OK
- BaF_2 is an excellent crystal candidate: rad hard, has fast UV (220 nm) component
  - A large but slow component centered at 300 nm can cause pileup
  - Efforts to suppress:
    - Y doping suppresses the slow component
    - Develop UV sensitive, solar-blind photosensors
  - Currently unfunded

Photons produced in BaF_2 vs. wavelength for different levels of Y doping



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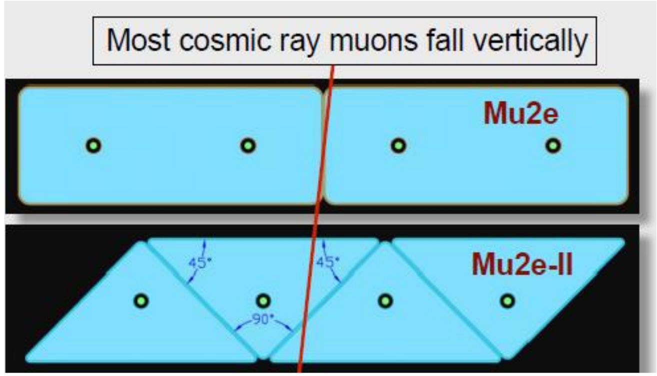
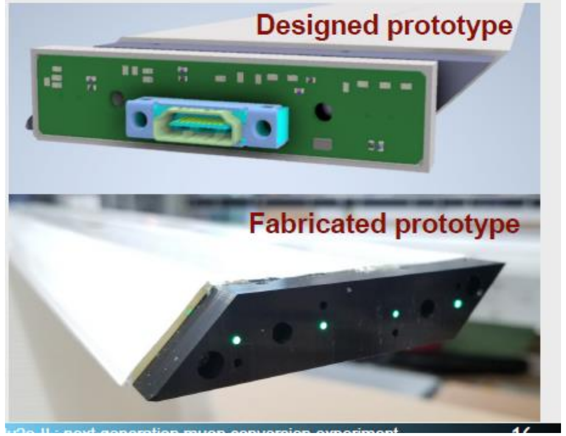
Mu2e-II Cosmic Ray Veto

- Mu2e-II will require an improved CRV
  - X3 more live time means will need x3 higher veto efficiency
  - Enhance light yield: thicker wavelength-shifting fiber, improved SiPMs, potting fiber in holes
  - Enhanced design using triangular-shaped counters, improved efficiency due to reduced gaps
    - A prototype has been designed
  - Enhanced instrumentation of holes in coverage
  - Increase shielding in key spots
    - Overhead to reduce neutrals (neutrons) in cosmic ray flux
    - To absorb cosmics that evade the CRV in the un-instrumented DS entrance aperture
    - Between the DS and the production and stopping targets to reduce noise hit rates in CRV





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Mu2e/Mu2e-II Background and Sensitivity

- Mu2e-II simulation with reduced straw wall thickness: 8 micron vs Mu2e 15 microns, improved CRV
  - Momentum resolution of Tracker improved from 140 keV to 100 keV
- Same Al target as Mu2e, assume BaF_2 crystals in first calorimeter disk
- Assumes 28 carbon spheres (0.75 cm radius) as pion production target
- CE energy acceptance window is reduced from 1.05 MeV → 0.85 MeV to reduce DIO background
- Assuming 5 years of data collection gives X10 improvement in sensitivity with <0.5 background counts

Results	Mu2e	Mu2e-II (5-year)	Required improvement
Backgrounds			
Decay In Orbit	0.144	0.263	Improved tracker resolution
Cosmics	0.209	0.171	Improved veto and enhanced shielding
Radiative Pion Capture	0.025	0.033	Improved extinction $< 10^{-11}$
Radiative Muon Capture	< 0.004	< 0.02	
Antiprotons	0.040	0.000	Beam energy below $\overline{p}$ threshold
Others	< 0.004	< 0.017	
Total	0.41	0.47	
N(muon stops)	6.7×10^{18}	5.5×10^{19}	
SES	3.01×10^{-17}	3.25×10^{-18}	
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}	
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}	

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Summary Mu2e-II

Mu2e-II offers compelling science beyond Mu2e

- **X10 improvement over Mu2e provides in most NP scenarios the deepest probe of CLFV for currently planned experiments**
- **Offers additional insights into New Physics parameter space, independent of Mu2e outcome**
  - If Mu2e discovery: Mu2e-II achieves precision to explore underlying NP operators
  - If Mu2e limits: Mu2e-II extends sensitivity of $R_{\mu e}$ another order of magnitude, energy scale of NP by factor 2

Mu2e-II can be an important part of FNAL program enabled by an upgraded PIP-II

- **Science goals can be achieved utilizing an upgraded Mu2e and additions to the PIP-II complex**
  - Experimental concept established using detailed simulation and full sensitivity estimate
  - PIP-II, with upgrades, is capable of providing required pulsed proton beam
  - Leverages significant investment in Mu2e and Fermilab Muon Campus
- Asking P5 endorsement of physics goals and enabling critical R&D

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Summary Mu2e

Mu2e will produce x10000 improved sensitivity to muon to electron conversion

- **Strong endorsement from P5 in 2014**
  - "Recommendation 22: Complete the Mu2e and muon g-2 projects"
- **Important component of the Fermilab program into the next decade**
- **Major step forward in the search for charged lepton flavor violation**
  - Provides one of the deepest probes of NP related to CLFV
- **Run 1 scheduled in 2026 before LBNF/PIP-II shutdown**
  - Goal: 10% of total data set and x1000 improvement in sensitivity over present experimental limit
- **Run 2 after LBNF shutdown expects to reach final x10000 goal in 4 years of running**
- **Asking P5 for strong endorsement of Mu2e physics goals**

Mu2e Collaboration

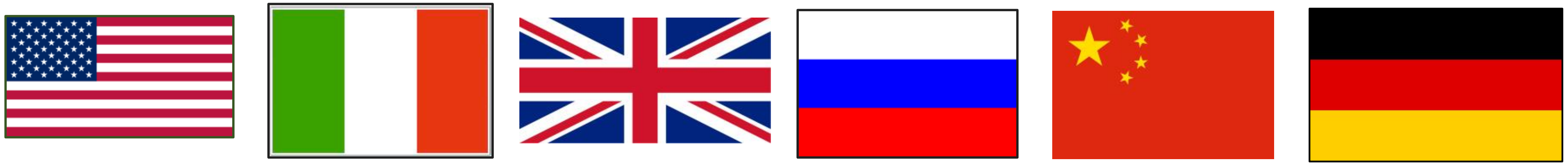
END

Mu2e Collaboration

Over 230 Scientists from 37 Institutions

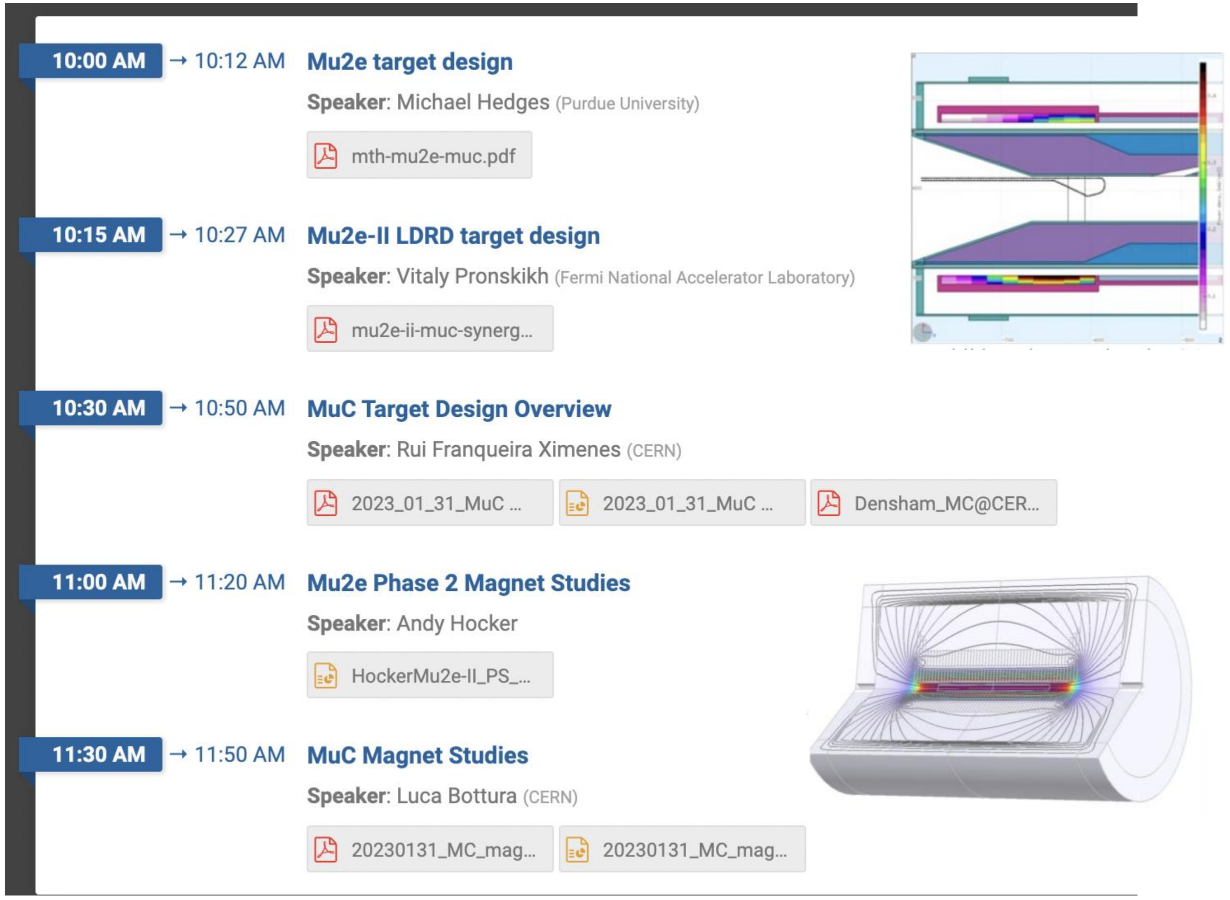
Non-US highlighted In red

Argonne National Laboratory, Boston University, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University,, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University



Mu2e-II / Muon Collider R&D Synergy

- Mu2e and the Muon Collider initiative have large areas of overlap, particularly with high power targets, cooling, and solenoids that need to live in intense environments
- Mu2e gave a presentation at the last Muon Collider Collaboration meeting and a followup workshop was held January 31
- We look forward to collaborating closely in the future.
- Mu2e is an excellent place to get started on intense muon beams now!



10:00 AM → 10:12 AM **Mu2e target design**
Speaker: Michael Hedges (Purdue University)
mth-mu2e-muc.pdf

10:15 AM → 10:27 AM **Mu2e-II LDRD target design**
Speaker: Vitaly Pronskikh (Fermi National Accelerator Laboratory)
mu2e-ii-muc-synerg...

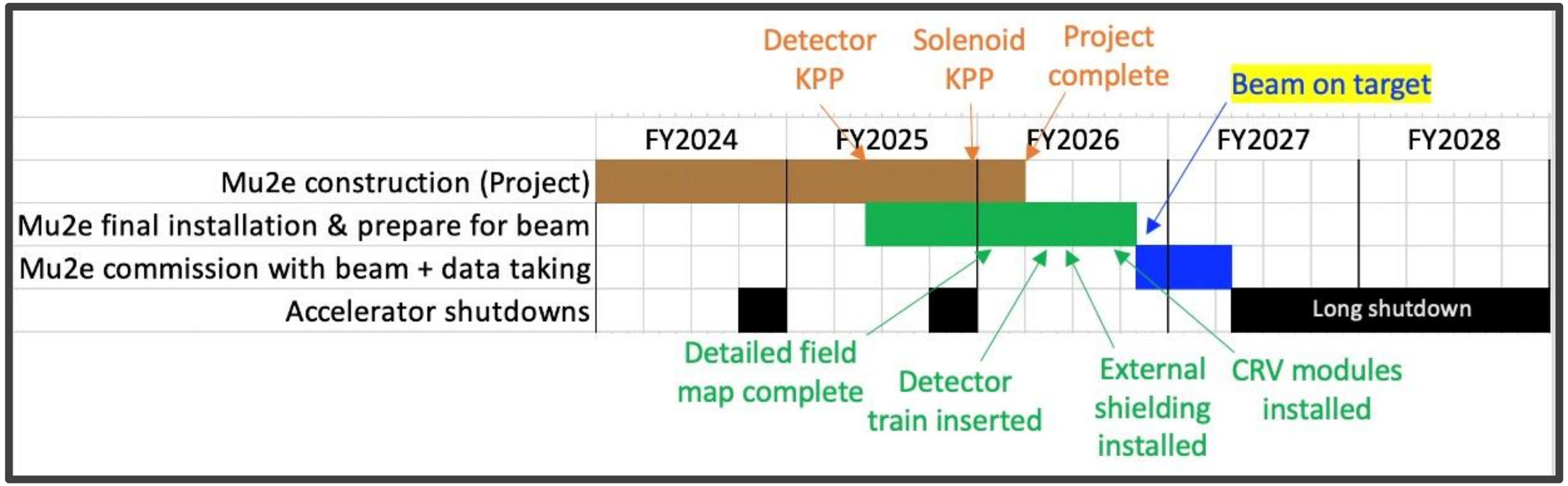
10:30 AM → 10:50 AM **MuC Target Design Overview**
Speaker: Rui Franqueira Ximenes (CERN)
2023_01_31_MuC ... | 2023_01_31_MuC ... | Densham_MC@CER...

11:00 AM → 11:20 AM **Mu2e Phase 2 Magnet Studies**
Speaker: Andy Hocker
HockerMu2e-II_PS_...

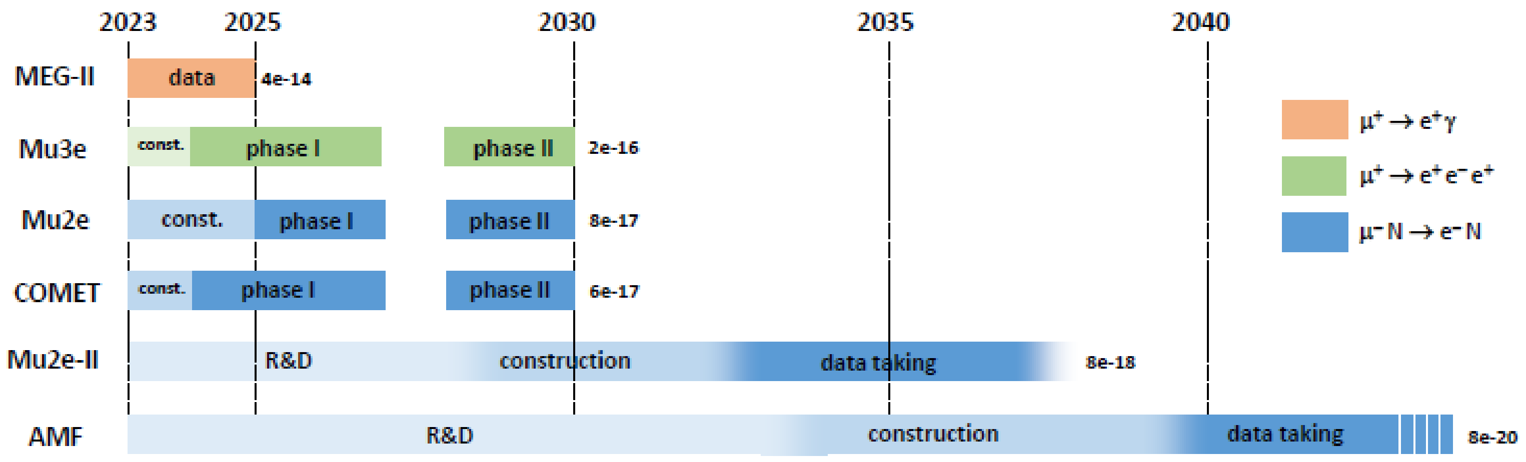
11:30 AM → 11:50 AM **MuC Magnet Studies**
Speaker: Luca Bottura (CERN)
20230131_MC_mag... | 20230131_MC_mag...

Schedules

- Mu2e

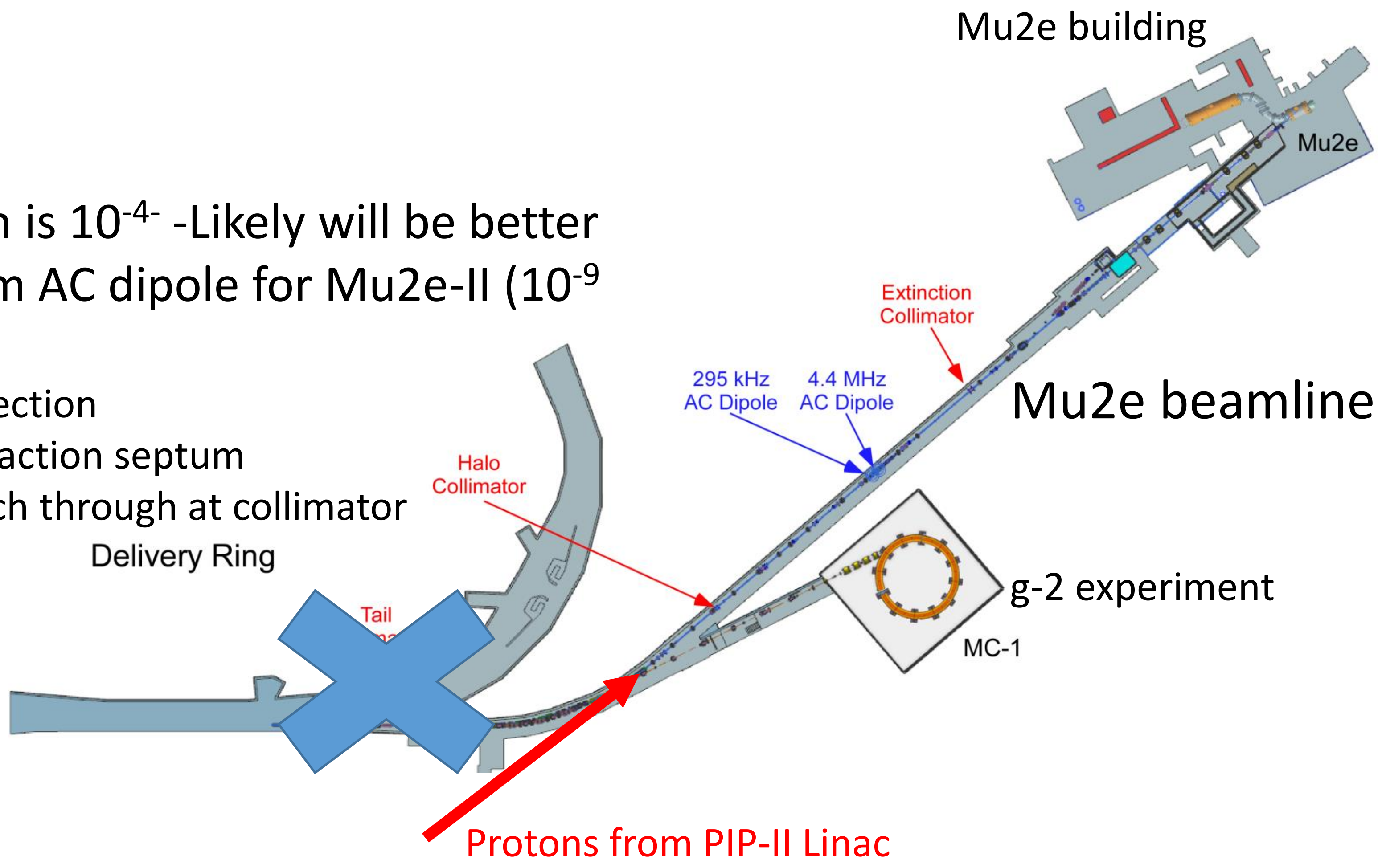


- Charged Lepton Flavor Tests



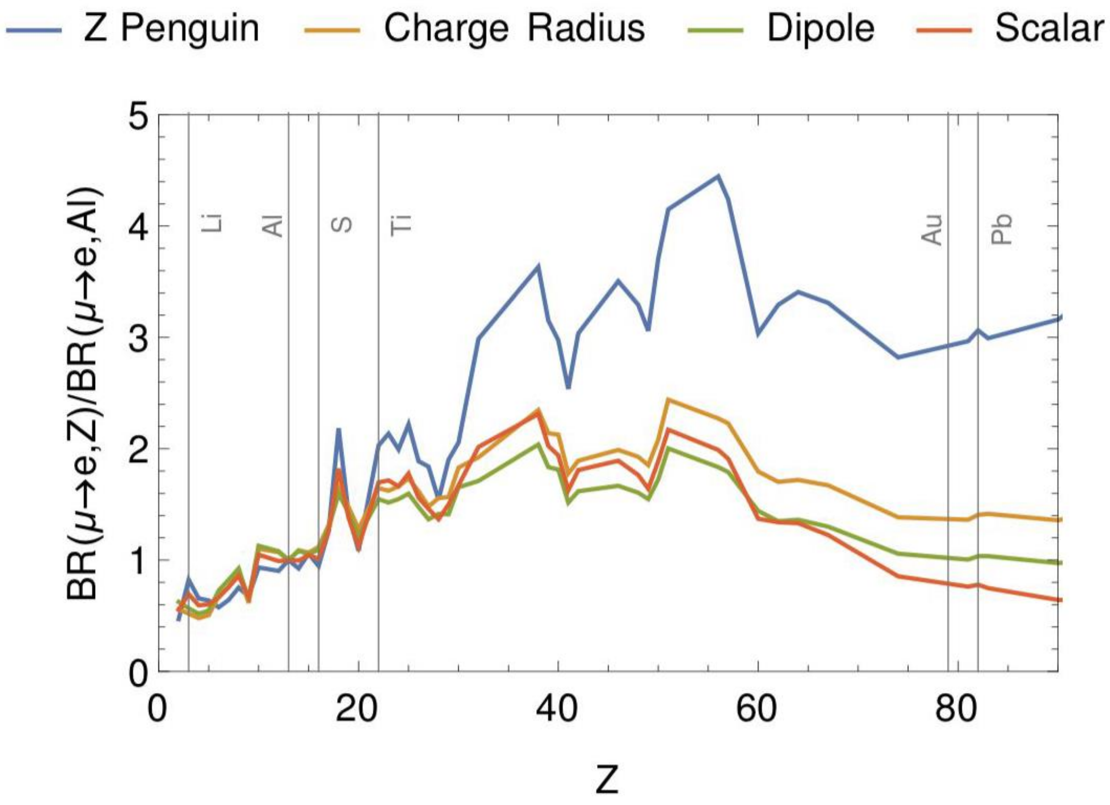
Mu2e-II Extinction

- Extinction is measure of out-of-time beam
- Mu2e-II requires extinction < 10^{-11}
  - cf Mu2e requirement < 10^{-10}
- Mu2e-II will use Mu2e AC
- PIP-II Linac extinction specification is 10^{-4-} -Likely will be better
- Expect improved performance from AC dipole for Mu2e-II (10^{-9} with safety margin)
  - Lower momentum means larger deflection
  - No beam halo from Mu2e's slow extraction septum
  - Lower momentum means lower punch through at collimator



Stopping Target

Mu2e Stopping Target
- Complete
- 37 Al foils, 0.1 mm thick
- 2 cm spacing,
- 43 mm diameter hole
- Suspended by 3 spokes of 3 mil W wire



Mu2e-II: On-going studies of other target materials
- Theory: examine sensitivities to structure of LFV operators
- Simulate experimental sensitivity for various target thicknesses and geometries
- Potential low-Z candidates: Li, Al, Ti, V
- High-Z targets have short lifetimes and do not survive into the delayed measurment window

Project Cost and Schedule Benchmarks

- Mu2e
  - Project is 85% complete.
  - Mu2e TPC: $315.7M
  - Mu2e Project is fully funded as of March 2023
  - Contingency > 40% on work to go
  - Run 1 2026
  - Run 2 2029-2033
- Mu2e-II Project cost estimate ~$150M Current year dollars plus cost of upgrades to PIP-II
  - Schedule: Request for R&D design continue
  - Cost does not include cost of upgrade of PIP-II

International Contributions to Mu2e

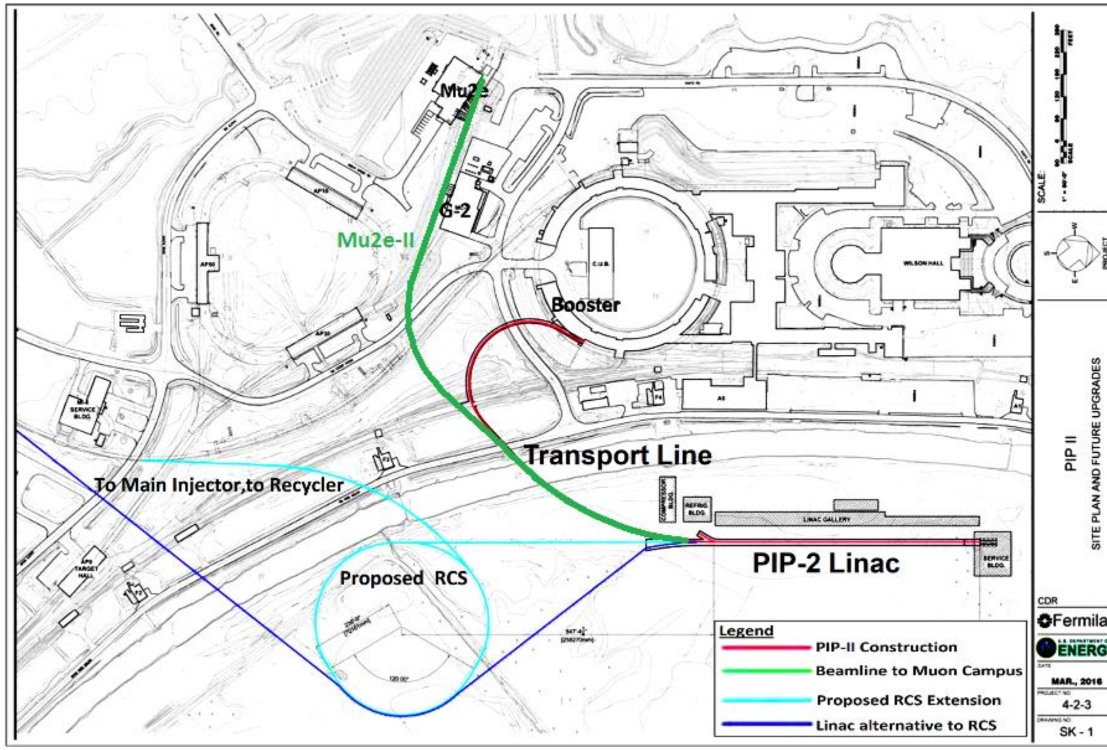
- UK contributions
  Production Target R&D
  Stopping Target Monitor - Germanium detectors plus readout/integration with TDAQ (detector delivered, readout/integration in progress), FPGA programming and front-end firmware, Labor associated with these activities

  Italy contribution
  Transport solenoid coil fabrication oversight
  Shared calorimeter CsI crystal procurement
  All calorimeter photosensors
  Front-end and back-end electronics
  Back-end electronics and power
  Calorimeter mechanical structure and cooling manifolds
  Laser calibration system
  Prototyping and QA/QC including radiation, B-field tests, etc.
  Labor associated with these activities
- HZDR Dresden
  - Background rates, and radiation dose calculations for all elements of the experiment
  - Led multiple beam tests of calorimeter and stopping target monitor detectors
- Russia
  - Simulations, detector R&D for Mu2e-II, calorimeter electronics QC/QA

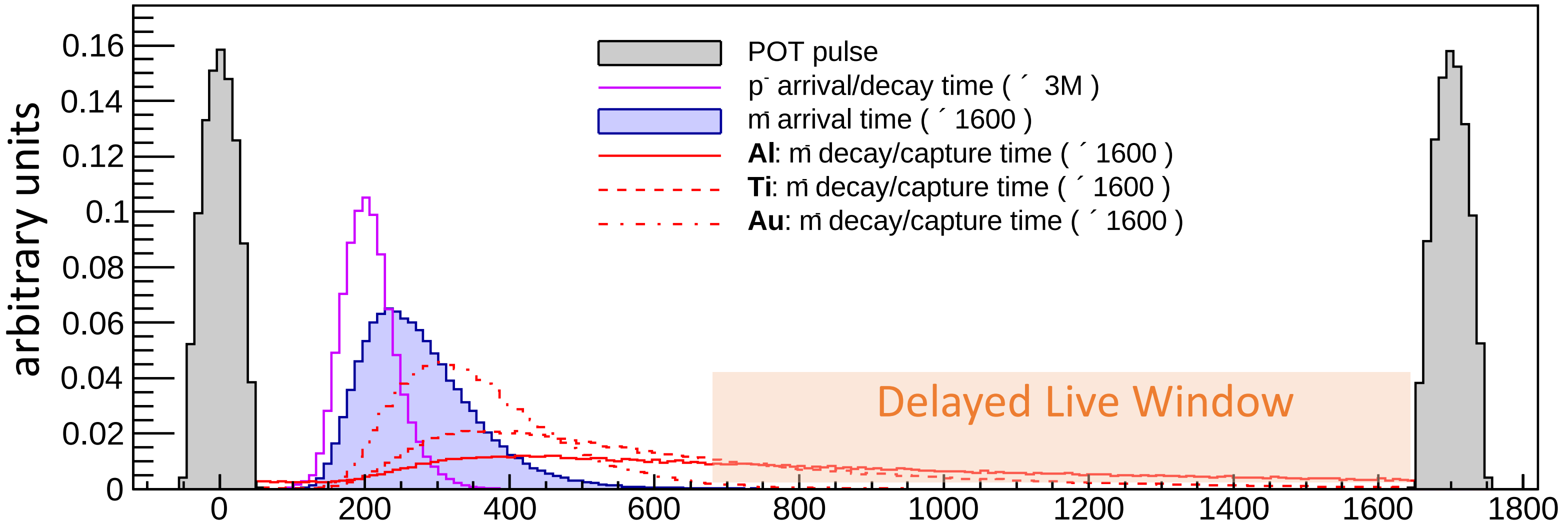
Mu2e-II beamline using PIP-II protons

- Needs upgrade of PIP-II: beam line from Linac directly to Mu2e
  - Eliminates Booster-Recycler-Delivery Ring, resonant extraction
  - Expect pulse intensity to be significantly more stable with less halo
- Can use any PIP-II Linac energy under discussion (0.8-2 GeV , higher is better)
- PIP-II has complete flexibility on what pulses to deliver, ideally suited to Mu2e-II needs
  - Neutrino program uses only small fraction of pulses

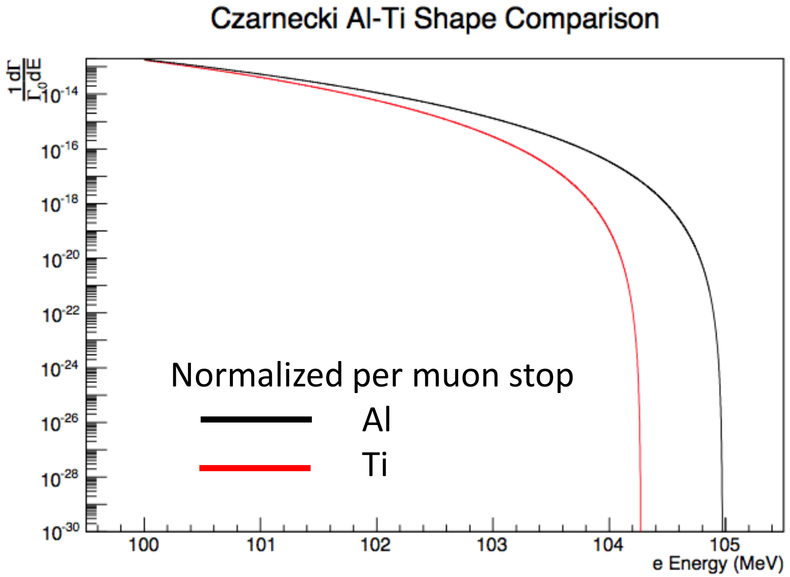
- Example Mu2e-II beam:10 Linac pulses 100 kW @800 MeV produces a 62 ns wide proton pulses
  - 62 ns width vs 200 ns (Mu2e) is improvement
  - Spacing (1693 ns) could be adjusted
  - Duty factor would be >90% vs 25% for Mu2e
  - At 800 MeV factor 7 increase in average muon stop rate, factor of 3 increase in instantaneous rates
  - Muons/watt increases significantly at 2 GeV



Feasibility of Mu2e-II Experimental Concept



K. Knoepfel, *et al.*, arXiv:1307:1168 (2013).



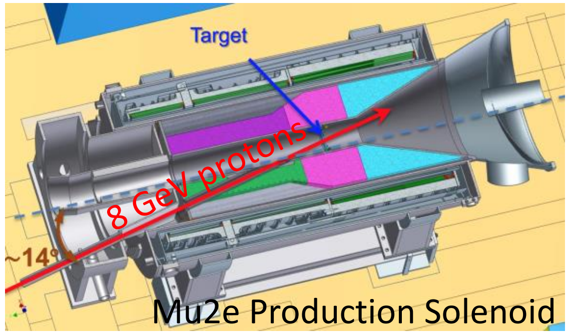
Element ($^A_Z N$)	Density (ρ_N)	Decay fraction (f_N)	Lifetime (τ_N)
$^{27}_{13}$Al	2.70 g/cm^3	0.39	864 ns
$^{46-50}_{22}$Ti	4.51 g/cm^3	0.15	329 ns

A. Czarnecki, X. Garcia I Tormo, & W.J. Marciano, PRD 84 (2011) 013006.

- Aluminum & Titanium stopping targets investigated
  - Accounted for differences in density, decay fraction, end-point energy, DIO spectrum
- **Total background can be kept ~1 event**
  - **Discovery sensitivity continues to scale linearly with single-event-sensitivity**

Required R&D – Beam delivery

- Main issue: need to steer 0.8 GeV beam to hit the production target
- Internal studies (mu2e-doc-db-16205, 16328) have found solutions
  - Require modifications to various components of target station region
  - Exact solution will depend on details of production target & solenoid
  - Now beginning studies of stripping & secondary extinction options



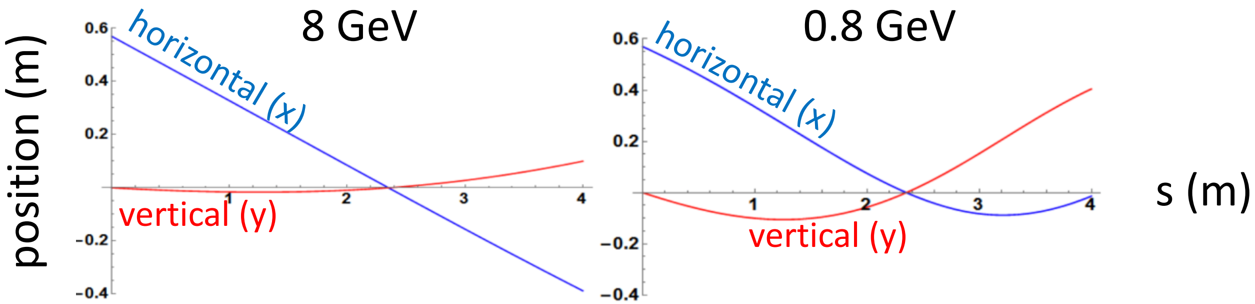


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at =2.35m

TABLE 1. Trajectories for 8 GeV and 800 MeV protons. (target at s=2.35m)

Position	8 GeV (x, y)	8 GeV (x', y')	800 MeV (x,y)	800 MeV (x', y')
s=0 entrance	0.57, 0.0 m	-13.6 °, -1.4°	0.57, 0.0	-11.4, -8.3°
s=2.35 target	0.0, 0.0 m	-13.6°, 1.8°	0.0, 0.0	-9.6°, 10.9 °
s=4m exit	-0.39, 0.08 m	-12.7°, 5.1 °	-0.01, 0.40	10.2 °,11.4 °

Table & Figures from Dave Neuffer

Mu2e-II vs. Mu2e proton beamlines

Parameter	Mu2e	Mu2e-II	Comment
Proton source	Slow extraction from DR	PIP-II Linac	
Proton kinetic energy	8 GeV	0.8 GeV	
Beam Power for expt.	8 kW	100 kW	Mu2e-II can be increased
Protons/s	6.25×10^{12}	7.8×10^{14}	
Pulse Cycle Length	1.693 μs	1.693 μs	variable for Mu2e-II
Proton rms emittance	2.7	0.25	mm-mrad, normalized
Proton geometric emittance	0.29	0.16	mm-mrad, unnormalized
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV	
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}	
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}	
Stopped μ per cycle		1.2×10^{5}	
Stopped muons per second	9.9×10^{9}	7.1×10^{10}	

Closed caption box size

Expression of Interest – Mu2e-II

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

- Submitted to PAC 09 February 2018
- arXiv:1802.02599, Fermilab-FN-1052
- **130 Signatories, 36 Institutions, 6 Countries**

Expression of Interest – Mu2e-II

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

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Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Abstract

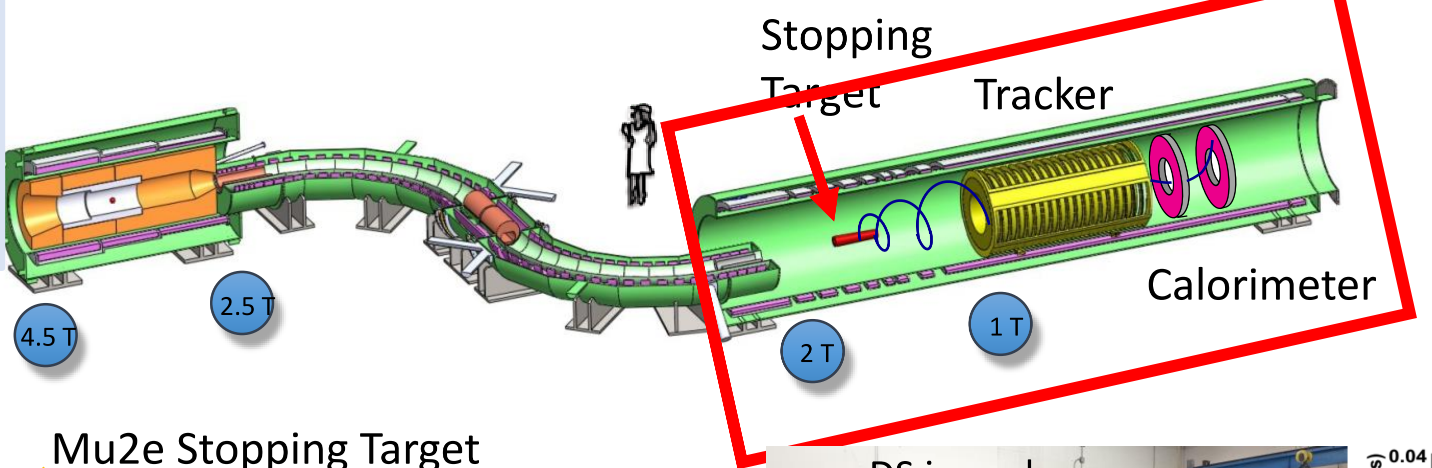
We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

"The PAC recommends the Mu2e-II proponents to identify the most relevant and urgent R&D items for the detector. The PAC endorses the Mu2e-II request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources".

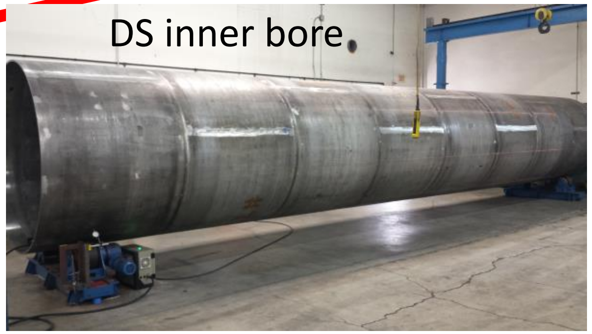
Mu2e Detector Solenoid

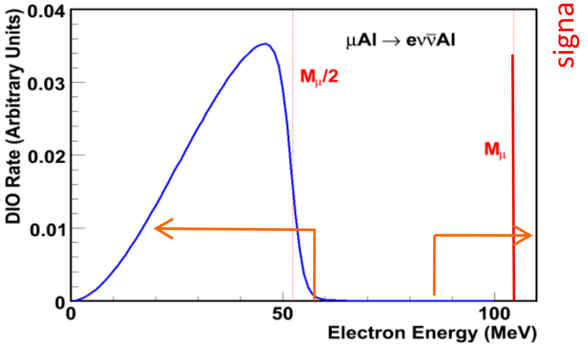
10/11 DS coils wound and epoxied
Cold mass cryo supports prepared
Delivery to Fermilab expected Feb 2024
(On critical path)

DS11 coil being wound



Mu2e Stopping Target
- Complete
- 37 Al foils, 0.1 mm thick
- 2 cm spacing, 7.5 cm radius
- 43 mm diameter hole
- Each foil suspended by 3 spokes of 3 mil W wire





“Hollow” tracker has very small acceptance for Michels and high acceptance for high-E signal